# PRIORITIZING LOW STRESS BICYCLE ACCESSIBILITY IN BALTIMORE

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# TABLE OF CONTENTS


Table of Figures ..... iii

Table of Tables ..... iii

Introduction ..... 1

Literature Review ..... 2

- Accessibility ..... 2
- Bicycle Quality of Service ..... 4
- Bicycle Equity ..... 7

Project Context ..... 9

Methods ..... 12

- Data Sources ..... 12
  - Bicycle Network ..... 13
  - Business Data ..... 16
  - Demographic Data ..... 16
- Data Preparation ..... 16
  - Bicycle Network ..... 16
  - Business Data ..... 17
  - Demographic Data ..... 18
- Data Analysis ..... 22
  - Accessibility Performance Measures ..... 22
  - Demographic and Equity Analysis ..... 23
  - Project Prioritization ..... 24

Results ..... 27

- Baseline Results ..... 27
  - Service Area Size and Accessible Street Distance ..... 27
  - Business Accessibility ..... 34
- Project Prioritization ..... 39

Discussion ..... 46

- Service Areas ..... 46
- Business Performance Measures ..... 47
- Project Prioritization ..... 48
- Equity ..... 49

Conclusion ..... 50

Acknowledgment ....... 51

References ....... 51

Appendix A. Technical Documentation ....... 54

LTS Network ....... 54

Adding in Trails ....... 55

Preparing the Projects Layer ....... 55

Neighborhood Centroids ....... 56

Service Areas ....... 57

Appendix B. Project Rankings ....... 58

B1.1. PM 1: Ranked by cumulative service area gains across all affected neighborhoods ....... 58

B1.2. PM 1 normalized: Ranked by cumulative service area gains across all affected neighborhoods, divided by the length of the project (Top 10) ....... 61

B2.1. PM 2: Ranked by cumulative low-stress street distance gains across all affected neighborhoods (Top 10) ....... 61

B2.2. PM 2 normalized: Ranked by cumulative low-stress street distance gains across all affected neighborhoods, divided by the length of the project (Top 10) ....... 62

B3.1. PM 3: Ranked by cumulative total business accessibility gains across all affected neighborhoods (Top 10) ....... 62

B3.2. PM 3 normalized: Ranked by cumulative total business accessibility gains across all affected neighborhoods, divided by the length of the project (Top 10) ....... 63

B4. PM 4: Ranked by number of neighborhoods that gain access to four out of four business types (All 13 projects) ....... 63

B5. PM5: Ranked by number of neighborhoods that gain access to a supermarket when previously having no access (All 13 projects) ....... 64

B6. PM6: Ranked by number of neighborhoods that gain new access to a library when previously having no access (All 16 projects) ....... 64

B7. Ranked by percent of black residents across all affected neighborhoods (Top 10) ....... 65

B8. Ranked by percent of Hispanic residents across all affected neighborhoods (Top 10) ....... 65

B9. Ranked by percent of non-Hispanic white residents across all affected neighborhoods (Top 10) ....... 66

B10. Ranked by percent of residents in poverty across all affected neighborhoods (Top 10) ....... 66

B11. Ranked by percent of households with no vehicle across all affected neighborhoods (Top 10) ....... 67

## TABLE OF FIGURES

Figure 1. Baltimore Neighborhood Demographics: Percent Black Population .......... 10
Figure 2. LTS 4 Barrier .......... 13
Figure 3. Bicycle Network .......... 14
Figure 4. Recommended Projects .......... 15
Figure 5. Business Locations .......... 18
Figure 6. Baltimore Neighborhood Demographics: Racial/Ethnic Distributions .......... 20
Figure 7. Baltimore Neighborhood Demographics: Poverty Rate .......... 21
Figure 8. Baltimore Neighborhood Demographics: Zero-Vehicle Households .......... 22
Figure 9. Select Neighborhoods with No Service Area .......... 28
Figure 10. Spatial Distribution of Accessible Area and Street Distance .......... 29
Figure 11. Select Neighborhoods with Large Service Areas .......... 30
Figure 12. Mid-Town Belvedere and Dunbar-Broadway Baseline Service Areas .......... 31
Figure 13. Blythewood Baseline Service Area .......... 32
Figure 14. Demographic Variation for Performance Measures 1 and 2 .......... 33
Figure 15. Spatial Distributions of Number and Diversity of Accessible Businesses .......... 35
Figure 16. Demographic Variation for Performance Measures 3 and 4 .......... 36
Figure 17. Spatial Distributions of Accessibility to Each Business Type .......... 37
Figure 18. Demographic Variation for Performance Measures 5 and 6 .......... 38
Figure 19. Short-Term Priorities, Bike Master Plan 2015 .......... 40
Figure 20. Projects with No Impact .......... 41
Figure 21. Projects Highly Ranked by Performance Measures and/or Demographics .......... 45
Figure A22. Setting LTS Restrictions .......... 54
Figure A23. Selection of Underlying Street Links by Shared Location with Project Recommendations – Pre- and Post-Processing .......... 55
Figure A24. Snapping Inconsistencies on Streets with Medians .......... 56
Figure A25. Service Area Settings .......... 57

## TABLE OF TABLES

Table 1. Business Data Selection .......... 17
Table 2. City of Baltimore Demographics .......... 19
Table 3. Performance Measures .......... 23
Table 4. Accessibility Gains for Each Affected Neighborhood due to a Single Project .......... 25
Table 5. Demographic Impact by Neighborhood due to a Single Project .......... 26
Table 6. Project Rankings by Performance Measure .......... 27
Table 7. Descriptive Statistics for Performance Measures 1 and 2 .......... 28
Table 8. Descriptive Statistics for Business Accessibility .......... 34
Table 9. Top Ranked Projects by Performance Measures .......... 42
Table 10. Rankings across Multiple Measures .......... 43
Table 11. Rankings across Multiple Indicators of Disadvantage .......... 44
Table A12. Centroid Adjustment .......... 56

# INTRODUCTION

One goal of bicycle planning is to make cycling a viable form of urban transportation for anyone, whether out of choice or necessity. In many cities the bicycle's low mode share results in and is a reflection of fragmented and opportunistic planning efforts limited by lack of data and funding—thus perpetuating the auto-centric nature of transportation planning. Fortunately, more systematic planning efforts are being undertaken in across the country as more cities develop bicycle master plans. Planners strive to match infrastructure supply with cycling demand. On the transportation supply side, tracking system-wide measures of bicycle network quality of service is crucial for comprehensive bicycle planning and project prioritization. Similar to how road networks are categorized by functional class and graded on Level of Service (LOS) provided to motorists, bicycle planners use quality of service measures to quantify how comfortable the network is for users.

On the demand side, individuals use the bicycle network to access the places and activities that sustain and enrich their lives. Transportation infrastructure is built to facilitate access to desired destinations rather than to allow travel itself. Accessibility measures can be used quantify the degree to which desired places can be reached using a certain means of transportation. However, infrastructure, itself, may also be valued as a symbol of investment into a particular neighborhood.

Planners must consider whether investment is equitably distributed, but properly understanding and addressing equity impacts requires careful attention to data and methods. Building infrastructure based on peak-hour bicycle volume counts could result in prioritizing commuter routes used by existing cyclists. This approach could neglect routes taken by individuals who do not work in major job centers, do not cycle during peak hour, or cycle for non-work purposes; it could also miss out on opportunities to facilitate cycling among new or hesitant travelers who are especially sensitive to the perceived safety and comfort of facilities. Likewise, planning with data collected from smartphones would ignore cyclists without certain technologies. As Le Dantec et al. note, the communities that may be most underserved or most impacted by bicycle planning decisions may not be visible in certain types of data (2016). An accessibility-based approach considers opportunities to reach destinations, regardless of whether travel survey or bicycle count data shows evidence of these opportunities being realized. Transportation planning literature has covered a variety of ways to evaluate the accessibility, bikeability, and equity of bicycle networks and transportation systems more broadly, and ways to tie outcomes to project prioritization. However, many studies tend to focus on only one or two of these aspects. In contrast, this research fills a gap in the literature using accessibility performance measures to equitably prioritize bike projects that would improve quality of service, using the City of Baltimore as a case study.

The Baltimore City Department of Transportation (BCDOT) completed a Master Bike Plan in 2015. In addition, the completion in 2016 of a citywide quality of service analysis using Level of Traffic Stress (LTS) has created the perfect springboard from which to launch further GIS-based analysis. An opportunity exists to assess the performance of the existing and proposed network in terms of accessibility and equity—two concepts that are mentioned but not evaluated in the plan. The plan does not make clear the method used to prioritize projects, so this research offers an example of how projects could be prioritized to maximize accessibility and equity. The methods section develops six performance measures to establish the baseline level of accessibility to four types of commercial and institutional destinations for each neighborhood. The paper then evaluates the equity of performance measure outcomes using demographic indicators of disadvantage as an additional consideration for the prioritization process.

Additional motivations for developing this method are to explore how a department such as BCDOT could use their existing LTS network not only for visualization, but also for quantitative analysis at citywide and neighborhood levels, and assess accessibility despite data limitations. The Baltimore region has not had a household travel survey conducted since 2007, and it contains limited information about bicycle trips (personal communication, Baltimore Metropolitan Council staff, January 19, 2017). Given the lack of recent empirical data for bicycle trip demand and route choice, a cumulative opportunities approach is useful for evaluating the degree to which the bicycle network can potentially serve anyone, but especially disadvantaged communities, regardless of whether they currently travel by bicycle. The method is tailored to the City of Baltimore's data but could by adapted for other places. In a public process, the number and types of destinations in the accessibility analysis and the indicators of disadvantage could be chosen based on community needs and perceptions.

# LITERATURE REVIEW

This section seeks to weave together several threads in the literature about transportation accessibility, analyzing and planning bicycle networks, and bicycle equity. Accessibility analyses are more commonly conducted for motor vehicles and transit, and often for accessibility to jobs. Additionally, accessibility has been used a metric to assess equity or to assess system performance; less often it is used to help prioritize projects. Bicycle accessibility is sensitive to the suitability or comfort of streets, thus requiring an added step of analyzing and classifying bicycle networks, often by using a quality of service measure. The distribution of existing quality of service would inform accessibility results and performance measure outcomes. However, much of the bicycle accessibility literature has not focused on linking findings to equity issues. Against this backdrop, it is important to understand how researchers have used accessibility, especially non-work accessibility, to evaluate equity, measure system performance, and prioritize bicycle projects. The role that quality of service measures such as Level of Traffic Stress (LTS) have played in these analyses is reviewed. Since bicycle accessibility and network quality research is often framed in terms of sustainability and livability, the literature review also covers how some researchers have discussed or analyzed equity as it relates to bike infrastructure, developing bikeable cities, and the bike movement more broadly.

## Accessibility

Accessibility, or the potential for people to reach desired destinations, has been identified as a goal of transportation planning since the 1950s. Accessibility measures have primarily been auto-based and focused on work destinations, despite the fact that travel mode and access to non-work activities influence quality of life (Grengs, 2015; Iacono, Krizek, & El-Geneidy, 2010). No matter the mode, lack of accessibility to destinations can be a marker of social exclusion and systematic disadvantage for certain demographic groups (Grengs, 2015; Páez, Gertes Mercado, Farber, Morency, & Roorda, 2010). Location-based measures quantify accessibility for a geographic unit, whether a traffic analysis zone (TAZ), neighborhood, or census block, whereas person-based measures quantify accessibility for individuals with certain characteristics including demographics, mode choice, and travel schedule. Location-based accessibility measures are more commonly used, as they do not require specificity about individual characteristics and can be comparable across a city or region to identify underserved areas. Though putting people at the center of accessibility is ideal, infrastructure investments take place in physical space, making location-based measures appropriate if paired with a demographic analysis. Three common location-based measures are based on the gravity model, utility functions, and cumulative opportunities ("Transportation Geography and Network Science/Accessibility," 2013).

The gravity-based measure, in which accessibility is positively influenced by the attractiveness of the destination and negatively influenced by impedance (time or distance) to reach the destination, has been adapted to measure non-work accessibility by Grengs (2015) and non-motorized accessibility by Iacono et al. (2010). In both studies, attractiveness factors were estimated using number of employees, sales volumes, or population, and impedance functions were estimated for destinations including shopping, schools, and restaurants using travel demand modeling software and household travel survey data. Grengs found that auto accessibility varies by trip purpose in his case study of Detroit, with white, suburban residents of the racially-segregated city enjoying disproportionate accessibility to supermarkets, in contrast to more equitable patterns of non-work accessibility (2015). Iacono et al. did not include a demographic analysis, instead focusing on quantifying non-motorized accessibility by estimating impedance functions for walking versus biking. They used a GIS street network for the Minneapolis-St. Paul region with the exclusive bike network incorporated into it instead of using the inadequately-scaled regional travel model network. Their method assumed use of the shortest-distance path and constant travel speeds. Grengs and Iacono et al. both contribute to the advancement of accessibility measures that paint a more inclusive picture of the links between transportation and land use. However, both studies noted limitations of their methods, including the lack of differentiation between quality of destinations and cost of goods and services (Grengs, 2015) and the inability to incorporate individual constraints such as bicycle ownership (Iacono et al., 2010) that create a more realistic view of accessibility.

Unlike the gravity model, which assumes that all people in a zone experience the same level of accessibility, utility-based measures account for individual preferences. Mesbah and Nassir (2014) developed a bike accessibility measure that incorporates bicyclist-preferred route choices and availability of multiple route options instead of simply using the shortest path between an OD pair. Route choice was modeled using a multinomial logit model where the cycling utility function was based not only on distance but also on type of facility (bike path, bike lane, curb-side lane, mixed traffic), slope of the roadway, and number of sharp turns. Because of lack of research for Brisbane, Australia, they used a utility function calibrated for San Francisco (Hood et al. 2011). The results highlighted areas of Brisbane that may have single high quality route but not many other route options and areas that do not have highest quality routes but do offer a diversity of options (Mesbah & Nassir, 2014). While utility-based measures can better represent individual accessibility than location-based measures, the need to develop (or borrow) a utility function can make this method impractical for many planners.

A simpler and thus more interpretable location-based measure is the cumulative opportunities approach. This method counts the number of potential opportunities, such as jobs, businesses, or parks, within a certain travel time or distance of predetermined point. NcNeil (2011) used the "20-minute neighborhood" concept to examine the viability of riding a bicycle to reach daily destinations including schools, libraries, shopping, services, dining, public transit, and recreational activities. The 20-minute concept was operationalized as 1 mile, 2 mile, and 2.5 mile service areas originating from twenty-six neighborhoods in Portland, OR, each centered on single location address. Drawing on findings from Broach, Gliebe, and Dill at Portland State University, McNeil incorporated network quality by assigning each link a “new effective length” based on the willingness of a travelers to ride longer distances on comfortable roads and shorter distances on stressful roads. For example, 1 mile of a bike boulevard was assigned the effective length of 0.82 miles, whereas 1 mile of a major arterial was assigned an effective length of 2.38 miles. Neighborhood bikeability was assessed using a scoring system that awarded more points to more frequent destinations according to the 2009 National Household Travel Survey, with reachable destinations in the outer rings (2 and 2.5 miles) of the service areas earning fewer points. The analysis was then rerun using a revised network based on the 2030 bicycle plan. While the 2030 plan build-out caused the accessible area to expand by over 15% on average for each neighborhood, McNeil notes that the relationship between service area size and bikeability varied between Downtown and East Portland because of land use patterns. Lack of bike accessibility to grocery stores was largest detractor from overall bikeabililty scores (2011).

The problem of food access emerged from both Grengs’ and McNeil’s findings, whereas Páez et al. (2010) use the cumulative opportunities measure specifically to link food inaccessibility to social exclusion. To overcome the two primary limitations of a location-based accessibility measures—lack of individual applicability and sensitivity to the choice of threshold—Páez et al. model the distance travelled using individual travel survey data. The resulting accessibility measure gives the total number of retail and fast food opportunities (out of 4,711 and 543 retail food and fast food establishments, respectively, across case study city of Montreal) accessible to a particular type of individual at a particular location. Groups such as low-income, carless, single-parent, or elderly travelers were compared to a reference group composed of under-65, higher-earning, members of non-single-parent households. Their findings showed that low-income travelers tended to have more accessibility to fast food than retail food outside the central city area. Páez et al.’s novel method of combining location-based and individual accessibility measures into a “representative activity space” allows planners to identify not only places, such as food deserts, but also person-place combinations that may exclude disadvantaged populations.

## Bicycle Quality of Service

Assessing accessibility for people on bicycles requires a way to differentiate between roads or facilities that are conducive to bicycle travel and those that are not. Unlike auto accessibility, the ability of a person to reach destinations using a bicycle network is sensitive both to land use and to the nature of the bicycle network, as characterized by connectedness, comfort, and availability of direct routes, among other indicators. The bicycle accessibility studies already discussed used methods such as assigning an effective length to each link based on comfort (McNeil, 2011) or incorporating bicycle facility types and steep slopes into a utility function (Mesbah & Nassir, 2014). However, these approaches were tailored to the analytical methods and data used by the researchers. Using a more standardized quality of service measure would allow the impedance created by high-stress or unsuitable roads to be included in an accessibility analysis that is more replicable and comparable to other cities.

Several bicycle quality of service measures have been developed to systematically classify how comfortable roadways feel for people on bikes. These include the Highway Capacity Manual's 2010 Bicycle Level of Service (BLOS), FHWA's Bicycle Compatibility Index (BCI), Bicycle Environmental Quality Index (BEQI), and Level of Traffic Stress (LTS), among others. BLOS is the bicycle counterpart to the industry standard for motor vehicles (LOS), but it requires data for ten roadway attributes that may not exist for a citywide network and was developed with only 120 participants who viewed and ranked video clips of different street types. Rybarczyk and Wu (2010) used BLOS as a supply-side indicator and crime, land use, and population data as demand-side indicators to develop a bicycle facility planning method using Milwaukee as a case study. However, their commercial land use data only included restaurant, taverns, bicycle stores, and coffee shops based on interviews with bicyclists. The authors found "low demand potential…in the inner city neighborhoods" because of high crime rates in those areas; they conclude that "neighborhoods with high demand potential could lend itself to infrastructure improvements to increase the safety of roads for bicyclists" (Rybarczyk & Wu, 2010). This type of approach would prioritize facilities for existing bicyclists of a particular sociodemographic background, with negative implications for equity.

BCI, which predates BLOS, is similarly data-intensive but does not classify intersections—thus missing a key potential barrier or 'weakest link'. Whereas BLOS and BCI assign each roadway link with an "A" through "F" grade, BEQI uses a more interpretable 100-point scale. Though it captures more aspects of comfortable bicycle travel such as bike lane connectivity, no turn on red signs, and bicycle/pedestrian-scale lighting, the San Francisco-specific model requires manual data collection and is less transferrable (Mingus, 2015).

LTS demonstrates the evolution of bicycle quality of service measures toward incorporating connectivity while attempting to use more publically available data. The growing popularity of LTS is evidenced by its development for cities including Baltimore, Washington, D.C., and Oakland (Semler et al., 2016) and its modification for Atlanta (e.g. Bearn, 2015; Mingus, 2015). Level of Traffic Stress (LTS) has four levels ranging from LTS 1 (lowest stress) to LTS 4 (highest stress) which are meant to correspond with Roger Geller's cyclist typologies based on stress tolerance ("interested but concerned child," "interested but concerned adult," "enthused and confident," and "strong and fearless"— the "no way, no how" type is assumed not to be influenced by increases in bicycle network comfort). The primary criteria are number of lanes and speed limit, as well as bike facility type, presence of parking, intersection characteristics, and other attributes where applicable. Separated bicycle facilities are assigned LTS 1, whereas the LTS rating for roads with bike lanes depends on the traffic and parking characteristics. The classifications for signalized intersections focus on conflicts with right-turning vehicles, while the classifications for unsignalized crossings are based on the speed, number of lanes, and presence of a median of the roadway to be crossed. LTS models the barrier effect of stressful intersections by applying the major street link's typically higher stress level to the links of approaching minor streets (Mekuria, Furth, & Nixon, 2012).

LTS can be used to measure the connectivity of a bicycle network and to identify low-stress "islands" created by high-stress barriers (Mekuria et al., 2012; H. Wang, Palm, Chen, Vogt, & Wang, 2016). Based on this concept, Wang et al. (2016) tested whether the size of a low-stress island can explain bicycle trip rates or bicycle mode share, with low-stress defined areas of the street network classified as LTS 1 or 2. The authors used the 2011 Oregon Household Travel Survey (OHAS) for two cities in Oregon and ACS

2007-2011 data, and associated each OHAS trip with origin and destination census blocks. Blocks that bisected, intersected, or bordered a low-stress island were the associated with their respective islands, and trips that took place within one island received a “low-stress connectivity” attribute. Households which did not take a trip on the survey day or did not own bicycles were removed, resulting in a final dataset of 660 households that were predominantly white and living in single family homes. Accessibility was defined as the “the amount of employment, activity and space accessible to households given their low-stress network” using 2010 Census population data and 2011 LEHD employment data (number of jobs). Results from the census commute mode data analysis suggest that the access to low-stress parts of the network is correlated with higher walk and bike mode shares. No correlation was found between job accessibility and bike mode share. A greater share of trips taken within low-stress islands were by those under the age of 18, women, and those making shorter trips or trips to school. However, this result could also be due to low-stress islands containing land uses that encourage walking and biking. Wang et al. note that one shortcoming of the Mekuria et al. LTS methodology is that it does not account for traffic volumes. Furthermore, spatial representations of low-stress islands may not align with “individuals’ personal cognitive map of their communities,” underscoring the importance of wayfinding in addition to bike infrastructure (H. Wang et al., 2016).

Building on the LTS method, Lowry et al. (2016) created a new, four-step method for prioritizing bicycle facilities. First, they classify the stress level of eleven road types using number of lanes and speed limit in a manner similar to LTS, and then use marginal rate of substitution (MRS) values developed by Hood et al. (2011) and Broach et al. (2012) to estimate the degree to which five types of bicycle facilities ranging from sharrows to protected bike lanes would reduce stress levels on each type of road. For example, a person would be willing to bicycle 120% further on a multi-use trail than to avoid the stress of a 5 lane, 35 mph road (LTS 4), but installing a protected bike lane would reduce stress by 75% to LTS 2 in Lowry et al.’s method (2016). Second, accessibility to twenty-one commercial, institutional, and recreational place types was assessed, with good accessibility defined as 1) at least two establishments of each destination type are reachable within 2 miles along low-stress roadways and 2) at least 70% of destination types are reachable. The percent of residents in each parcel experiencing good accessibility was a key metric, and it was calculated by solving all of the shortest low-stress paths within 2-miles of each parcel, using Seattle as a study area. Third, the contribution of each link to citywide accessibility was quantified in a centrality metric, where links that were used in multiple shortest paths had higher centrality. Fourth, the centrality metric was used rank projects by comparing the length-weighted average centrality across project links before and after the proposed project. Lowry et al. ranked 771 projects from Seattle’s Bicycle Master Plan by the change in average project centrality, finding that multi-use paths and protected bike lanes rose to the top of the rankings, whereas sharrows tended not to because they did not sufficiently reduce stress levels (2016). The researchers note that full build-out of the Bike Master Plan would improve accessibility for an “economically deprived and underserved” area with “poor accessibility by bicycle to important destinations,” but a more detailed demographic analysis is not included in the study (Lowry et al. 2016, pg. 134).

## Bicycle Equity

Though some studies have specifically tied accessibility to issues of equity and deprivation (e.g. Grengs, 2015 and Páez et al., 2010), these have been based on auto or transit travel. Research about bicycle accessibility and bicycle networks often compares drivers to bicyclists or stress-tolerant bicyclists to stress-intolerant bicyclists, without always delving deeper into demographic variations within these groups. The literature about bicycle equity is concentrated in an adjacent, though sometimes overlapping sphere.

Whereas concerns about transportation equity have traditionally been rooted in the environmental justice movement, concerns about bicycle equity are about where, how, and for whom public space for bikes is claimed. Transportation injustices are suffered by the populations, often minorities and low-income, that bear disproportionate burdens of transportation infrastructure investment: for example, physical displacement due to use of eminent domain for highway projects or negative externalities such as pollution and noise. Transportation justice seeks to address the three main ways that transportation planning has failed in terms of equity: 1) unequal distribution of the benefits of infrastructure investment, 2) unequal exposure to the burdens from infrastructure, and 3) unequal participation in the planning process. These failures have been addressed through Title VI of the Civil Rights Act of 1964 and subsequent guidance for its implementation provided by the Department of Transportation, as well as President Clinton's Executive Order 12898 issued in 1994 (Golub, 2016). Bicycle equity is primarily concerned with the first and third items: distribution of benefits arising from the claim of public space and procedural fairness.

On a theoretical level, Martens et al. (2016) grapple with the just distribution of bicycling benefits, asking what one person should give up so that another would be able to bike. They suggest that cycling can only be addressed through a distributional justice lens on the basis of two conditions: 1) the person to whom the ability to bike is 'distributed' must have a substandard level of accessibility, such as not owning a car due to financial circumstances, and 2) the cycling intervention that must improve substandard accessibility effectively and efficiently. This suggestion is grounded in Martens' (2012) earlier proposition that accessibility is the best reflection of the social meaning of transport and thus its benefits. As Martens would argue, though accessibility and mobility are two social meanings of bicycle transportation, only increased accessibility captures the potential for individuals to bicycle to desired destinations and accomplish desired actions, whereas increased mobility would only imply being able to bicycle more often and further—not the goal of utilitarian bicycle travel at all. Martens (2012) identifies individual accessibility as the correct focus of analysis, since people, not places, are the ones that benefit from the social meaning of transport goods. As previously discussed, assessing individual accessibility is a challenge, but the second condition for just distribution of bicycling benefits proposed by Martens et al. (2016) could be partially operationalized by investing in infrastructure that creates direct, comfortable routes to places that have typically been characterized by substandard location-based accessibility while also connecting to existing bicycle facilities.

However, Martens warns us not to focus only on distributing individual components of transport such as infrastructure while neglecting the distribution of accessibility, because "the social meaning of each of these parts stems from the social meaning of the overarching 'transport good'" (2012, pg. 5). In a similar vein, Golub (2016) describes how bicycle infrastructure is installed in a social context representing the intersection of the bicycle movement and transportation justice. Though infrastructure is a physical benefit of the bicycle movement, it is complicated by its association with gentrification and displacement, turning what is a benefit for most into a burden for some.

The complexity of capturing the social meaning of bicycle accessibility opens a gap between theories of distributional justice and the practice of assessing equity in bicycle transportation systems. For Martens, distributional justice would be based on “systematic assessment of the accessibility gaps between the transport disadvantaged and those groups in society that experience the highest accessibility levels”—which is difficult to institutionalize when LOS and travel demand modelling dominate the development of auto-oriented transportation systems today (2012, pg. 14). In contrast, analyses related to bike equity typically fall into two groups: 1) those that seek to measure the gentrification effects of bicycle infrastructure and 2) those that seek to measure the distributional equity of bike infrastructure.

Gentrifying impacts of bike infrastructure do not fit neatly into the EJ framework of benefits and burdens because the burden of rising housing costs, potential for displacement, and the psychological stress that accompanies infrastructure investment cannot be measured in the same way as pollution or noise, which can be assumed to affect everyone within a certain distance in the same way. Yet gentrification cannot be ignored when cities are sometimes seen as using active transportation infrastructure to attract “creative class” residents at the expense of disinvested communities. Despite popular media linking bicycle infrastructure investment and cycling culture to gentrification, there is limited empirical evidence of this phenomenon in the literature. To this end, Flanagan et al. (2015) created gentrification and cycling infrastructure investment indices to examine change in community composition from 1990 to 2010 in Chicago and Portland. The goal of the study is not to quantify gentrification, but rather to use regression analysis to assess whether privileged populations attract cycling infrastructure (and vice versa). The authors found a positive, non-linear correlation between the infrastructure and gentrification indices, with a 1% increase in population with college education and homeownership rate significantly predicting roughly a three standard deviation increase in cycling infrastructure in Portland and a 1% increase in white population significantly predicting a 1.4 standard deviation increase in infrastructure per square kilometer in Chicago. The results point to clear disparities in bike infrastructure investments and the need for infrastructure to support “bottom-up” reinvestment following community needs rather than “top-down” economic development schemes (Flanagan et al., 2015).

In the second group of analyses, access to bicycle infrastructure has been evaluated using several methods including equity indices (Prelog, 2015) and Lorenz curves (J. Wang & Lindsey, 2016). Prelog (2015) developed a two-part method for the League of American Bicyclists to investigate who benefits and who is disadvantaged by existing bicycle networks. The first part is the Bicycle Equity Index (BEI), which is composed of five indicators, standardized with z-scores and combined in a composite measure. Three indicators reflect transit-dependency—percent elderly (over 65), percent youth (under 18), percent zero-vehicle households—and two capture environmental justice—percent minority (non-white and/or Hispanic) and percent living in poverty. The BEI was applied to a case study in Chicago to investigate access to infrastructure. The second part of the method was an access coverage analysis. Access was measured using a quarter mile Euclidean buffer around bicycle facilities, calculating the percentage of each block group that fell within the buffer, and scoring it according whether the proportion of coverage was above or below the regional average. The BEI and infrastructure access components were overlaid to create a single map showing block groups with above-average access to infrastructure tended not to be the same block groups that scored highly as disadvantaged in the BEI. The method was then applied to the full build-out of Chicago's Cycling Plan 2020 to find the increase access for disadvantaged populations. One way to strengthen the coverage analysis would have been to use network distances instead of Euclidean buffers.

Wang and Lindsey (2016) also use a two-part method to examine the vertical equity of bikeways in Minneapolis, but in addition to evaluating access to infrastructure, they also conduct a more traditional cumulative opportunities analysis. Vertical equity of infrastructure access was assessed using Lorenz curves for various disadvantaged subpopulations, finding some evidence of inequity in access to trails. Wang and Lindsey then used ESRI ArcMap Network Analyst service areas to calculate "reachable areas" along "low-stress bikeways" (defined as local streets based on functional class, streets with on-street bike facilities, and off-street trails) within 3 miles. The service area for each block group is compared to the reachable area along the full street network and then used to calculate the number of accessible jobs lost due to using the bicycle network instead of the full street network. The types of jobs included were not stated. To assess vertical equity, the authors compared the average job-loss penalty among block groups, finding that block groups with the highest percentages of black, low-income, and zero-vehicle families experience the least job-accessibility loss. This paper exposes the weakness of using a single jobs measure to assess vertical equity, when it is unclear whether the jobs that are potentially accessible via the physical infrastructure of the transportation network are truly accessible via a societal system in which housing, education, and racial discrimination make jobs harder for disadvantaged populations to access.

As evidenced by these studies, theorizing and analyzing what it means for a bicycle system to be equitable has taken many approaches. Some approaches focus more on the proximity and effects of physical infrastructure, while others focus on the effects of being able to use that infrastructure, especially for commuting purposes. This research takes the second approach, but with the aim of quantifying the number and types of non-work activities that could potentially be accomplished by bicycle, and by whom.

## PROJECT CONTEXT

The City of Baltimore, MD is making fast strides in creating a bikeable city, despite having only adopted its first bicycle plan in 2006 (City of Baltimore, 2015)—relatively late compared to other American cities that have been engaging in bicycle planning since the 1970s. Since 2006, over 100 miles of bicycle facilities have been installed. Baltimore City Department of Transportation's (BCDOT) 2015 Bicycle Master Plan Update has outlined a vision for a safe and comfortable bicycle network to grow the bicycle commuter mode share from 1% to 8% by 2030 (City of Baltimore, 2015). This mode share target is the only quantified performance goal stated in the plan. Despite focusing explicitly first on commuter cycling and second on recreational cycling, the plan's goal to establish a bicycle-friendly business program implicitly values bicycling for non-work utilitarian travel as well. The 2015 plan does not explicitly mention the concept of equity or discuss demographic patterns in the racially-segregated city, except for providing a map showing the distribution of zero-vehicle households across the city and stating:

> "Limited approval of Bicycle facilities has resulted in facilities being concentrated largely in more affluent parts of the city, resulting in limited access for many residents…Some neighborhoods have excellent access to high quality bicycle facilities while others do not. In areas without good access, ridership numbers may decline or remain stagnant, while neighborhoods with good quality facilities consistently see ridership growth." (City of Baltimore, 2015, pg. 13)

An additional 253.6 miles of bicycle facilities are planned for a 15-year time period, with 15 projects listed as priorities, some of which have been built or are underway. The plan does not discuss how these projects were prioritized, though it does provide results from an online survey that received 1248 responses, primarily representative of people who already ride bikes, and a list of neighborhood open-house meetings held in 2013 (City of Baltimore, 2015)

The 2015 bike plan, along with Baltimore's roll-out of a city bike share program, have been criticized for serving primarily white and affluent areas of the city in what Morgan State University professor Lawrence Brown refers to as the "White L"—the downtown, Inner Harbor, and the north-south corridor running between the CBD, Johns Hopkins University, and the northern boundary of the city—while neglecting the "Black Butterfly"—the predominantly African American neighborhoods to the west, southwest, and northeast, as shown in Figure 1.

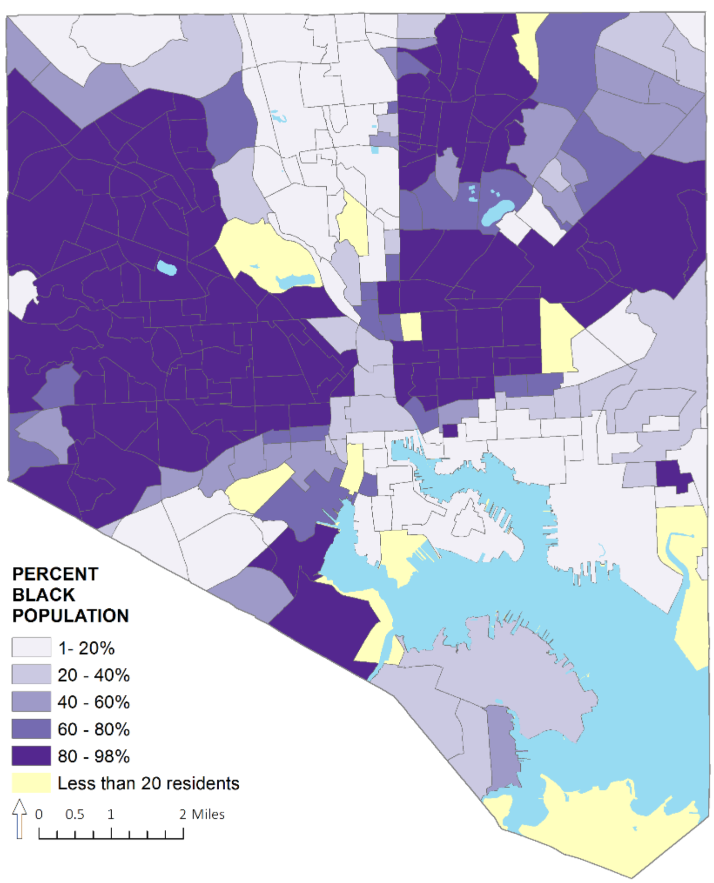


**Figure 1. Baltimore Neighborhood Demographics: Percent Black Population**

Brown states:

> "I want to talk about perhaps the primary reason we all should be very afraid of the racially discriminatory rollout of protected bike lanes and BikeShare in the White L: the psychological impact of racial segregation…when certain things exist in White neighborhoods but not Black neighborhoods, it sends Black folks living in redlined neighborhoods the subtle but powerful message that: 'That's not for us.'…By concentrating resources in the White L, this message of White exclusion is reinforcing over 100 years of history and undermines the fact that we MUST DESEGREGATE OUR CITY if Baltimore is to become a city where Black lives and Black neighborhoods actually matter" (Brown, 2016b, October 30)

Dr. Brown's focus on structural inequality contrasts with the measured rhetoric of the plan, which puts the onus on communities to approve new facilities. Yet community activists have mapped the location of bike lanes, bike share stations, and even bike racks in relation to census tracts with the highest and lowest percentages of black residents to demonstrate the existence of a "transit apartheid" (Brown, 2016a)

Two projects in the past five years reveal the differences in processes and outcomes for distinct communities: the removal of the Monroe Street bike lane and the opposition to, yet endurance of, the Roland Avenue cycle track. Installed in 2011 during a resurfacing project with no input from the community, the half-mile bike lane on Monroe Street went through the neighborhood of Mondawmin, which is 95% African American, with 21% living in poverty and 43% of households having no vehicle. As a result of pushback, the bike lane was removed five months later, though the community was open to finding other, more suitable streets for bike infrastructure (Shen, 2011b). The Monroe Street failure suggests that had BCDOT done outreach, it could have tapped into latent approval for the bike lane among some neighborhood residents; instead, a few community members with more power than the average bike lane user sought intervention from the district's city councilwoman (Shen, 2016).

On the other end of the spectrum, roughly 200 residents of the 82% white, affluent neighborhood of Roland Park attended a community meeting with roughly half of attendees opposed to a cycle track installed in 2015 over concerns about child safety and property values (Shen, 2015). The project was the first cycle track to be installed in the city, and BCDOT moved forward with it, because it had done its "due diligence" of over ten meetings with the community (Perl, 2015; Shen, 2015). Thus Mondawmin got the worst of both worlds: no public process and no bike infrastructure, while Roland Park, as half of its residents would see it, got the best. As the Mondawmin's former councilwoman, Belinda Conaway stated about Monroe Street, "They would never go into another community and treat them this way" (Shen, 2011a).

Bike planning can perpetrate injustice, or it can improve quality of life for disadvantaged communities. Baltimore's 2015 Bicycle Master Plan is ambitious but lacking in performance metrics, transparent project prioritization, and commitment to equitable outcomes. However, the completion in 2016 of a citywide quality of service analysis using the LTS method has laid the foundation for revised and supplemental planning efforts, like the Separated Bike Lane Network Plan released as an addendum in 2017.

# METHODS

This research draws inspiration from the literature while including several innovations to create a bicycle project prioritization method using both accessibility performance measures and demographic impact measures. These measures are calculated using the ESRI ArcMap Network Analyst service area function. A service area is a polygon that delineates the geographic extent of all routes away from an origin or to a destination along a network (as opposed to a straight-line buffer). It represents that area that is accessible to the average person at a specified starting point. In this study, bike accessible service areas were created for each of Baltimore's 278 neighborhoods by restricting travel to low-stress roads (LTS 1 and 2) and setting a distance threshold of two miles. This threshold was based on data from the National Household Travel Survey of 2009 showing that the average bicycle trip length is 2.3 miles, with non-work trip purposes such as shopping and personal business averaging 1.3 and 1.4 miles, respectively (Kuzmyak & Dill, 2012). Other accessibility studies that have used 1, 2, 2.5 or 3 mile cut-offs (e.g. Bearn, 2015; Lowry, Furth, & Hadden-Loh, 2016; McNeil, 2011). A type of automobile accessible service area was also created by generating the same 2-mile service areas without LTS restrictions; these are compared to the bicycle service areas to assess the accessibility deprivation potentially experienced by people lacking access to a vehicle.

The service areas themselves serve as performance measures, but more significantly they are used to capture the cumulative opportunities that can be reached by bicycle, thus generating additional performance measures based on accessibility to businesses and institutions. Whereas McNeil (2011) and Lowry et al. (2016) measured accessibility to a "basket" of over 20 destination types and Rybarczyk and Wu (2010) focused on four destination types thought to appeal to (a particular class of) cyclists, this research focuses on four destinations deemed essential for anyone's personal livelihood or for community quality of life: supermarkets, pharmacies, banks, and public libraries. Neighborhood accessibility is assessed in terms of the performance measures and the demographic variation across performance measures. The most significant innovation of the method is the use of these performance measures to prioritize bicycle projects. Instead of simply comparing the existing network to the full build-out of a bicycle plan or to a set of recommendations, this methodology quantifies the marginal accessibility gains expected to accrue from each proposed project separately. It also identifies the projects that would have the greatest impact on disadvantaged demographic groups.

## Data Sources

The analysis required three major data types: 1) bicycle network and project data, 2) business location data, and 3) demographic data and neighborhood boundaries.

## Bicycle Network

Routes comprising each baseline service area were generated using a bicycle network for the City of Baltimore. BCDOT provided its LTS street network; this was combined with off-street trails to create the final network dataset. BCDOT's LTS network was created in 2016 by applying the Mineta Transportation Institute methodology (Mekuria et al., 2012) to the city's street network. The multi-step classification process "made the most of assumptions regarding roadway widths and speed limits to filter out obvious LTS 1 and LTS 4 roads" (Semler et al., 2016). According to the weakest link concept, the highest LTS at an intersection was applied to all links going through it, so that neighborhood streets would not cross "through" high-stress barriers, shown in red in Figure 2. The resulting dataset contained an LTS value for every link. For the purposes of this study, the four LTS levels 1 through 4 were grouped into low-stress (1 and 2) and high-stress (3 and 4), consistent with other studies using the LTS methodology (e.g. Bearn, 2015; Wang et al., 2016). The LTS data file does not contain information on one-way streets, elevation, or turn restrictions that would affect the accuracy of GIS routing. Creating a more accurate network was outside the scope of this research, and other researchers have also made do with similar limitations (e.g. Boisjoly & El-Geneidy, 2016). The final network used in the analysis is shown in Figure 3.

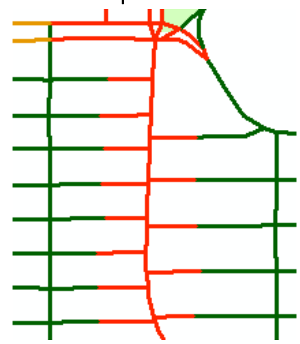

**Figure 2. LTS 4 Barrier**

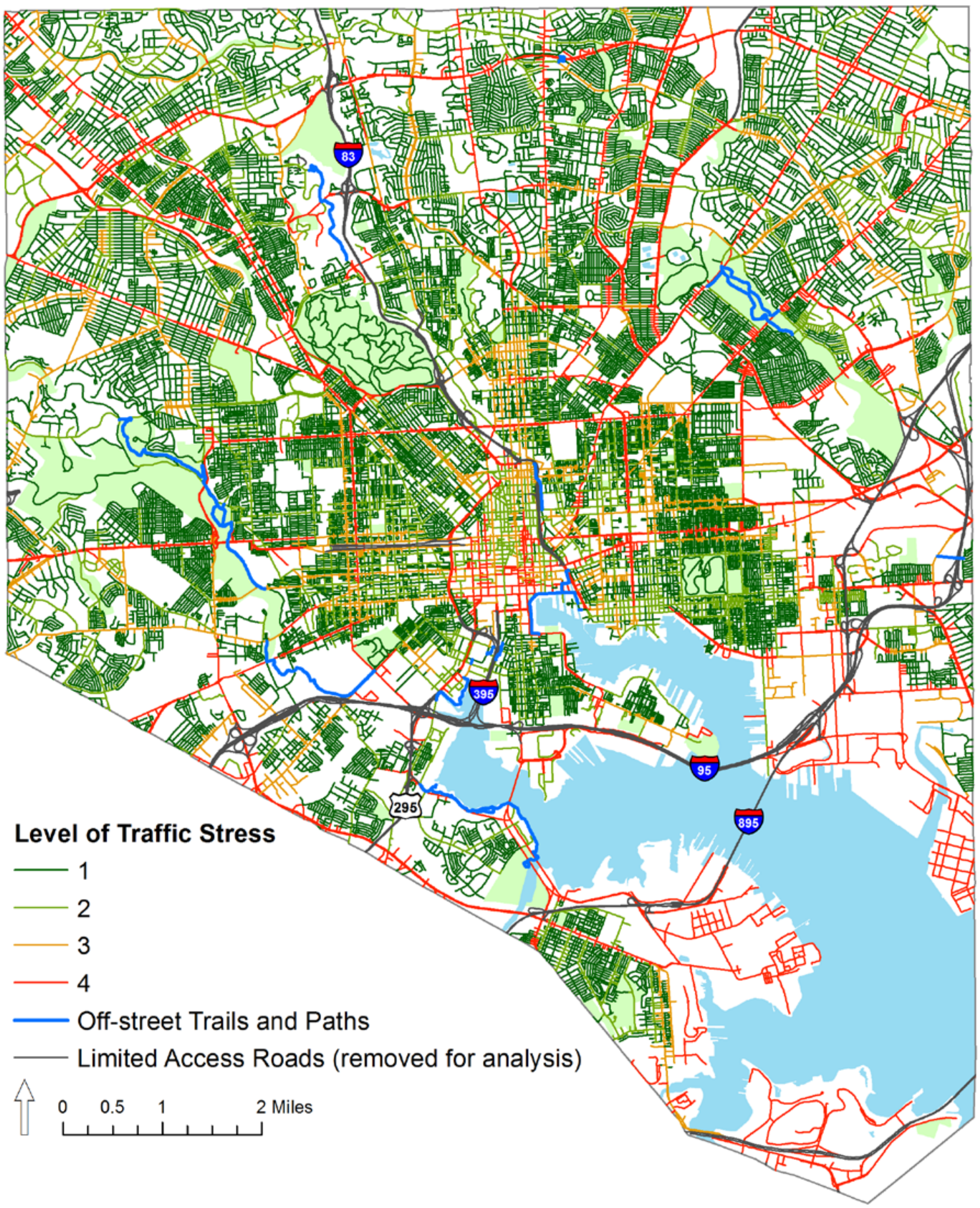


**Figure 3. Bicycle Network**

The project prioritization method relied on a working dataset of proposed and planned projects obtained from BCDOT's planning consultant. The GIS layer contains draft proposed projects from the Mayor's Bicycle Advisory Commission (MBAC) that was established to guide the implementation of Baltimore's 2015 plan, as well as recommendations from the consultant. Some of the projects in the file were already completed in 2016, such as the Maryland Avenue Cycle Track, but these were retained since reclassifying the LTS network was outside the scope of this research. Not all of the projects in the file have subsequently been approved. In total, the prioritization analysis used 106 recommendations for physically separated facilities, buffered bike lanes, and bike boulevards ranging from 0.05 mi (300 feet) to 2.88 miles in length, as shown in Figure 4.

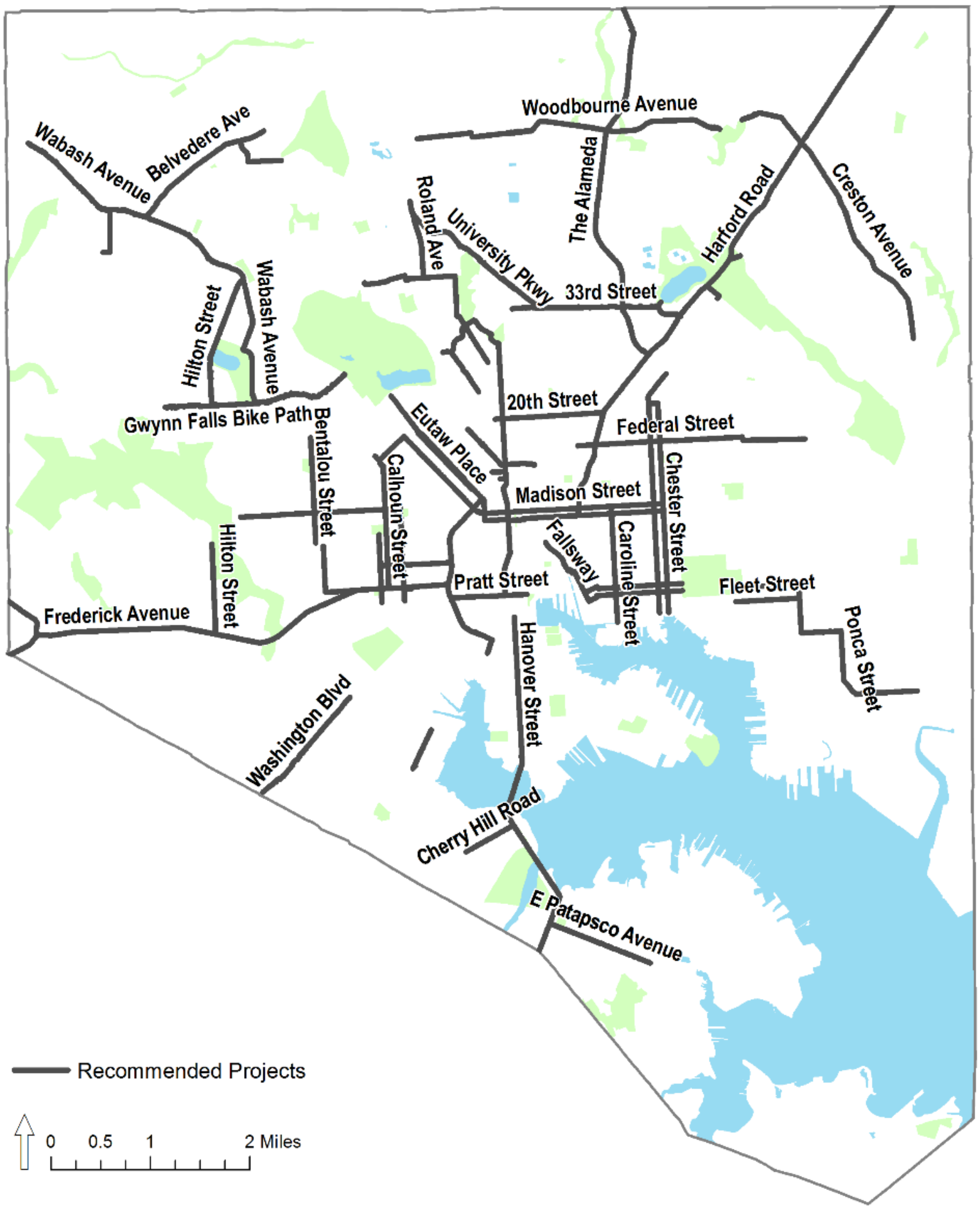


**Figure 4. Recommended Projects**

### Business Data

Business establishments located in the City of Baltimore were extracted from the ESRI Business Analyst dataset for 2015. Four types of businesses or institutions were chosen to reflect varying needs of Baltimore residents: supermarkets, pharmacies, public libraries, and banks. ESRI identifies business types using Infogroup's proprietary 8-digit NAICS-based code, which has 2 extra digits for detail (Esri, 2015).

### Demographic Data

Demographic data were obtained from the US Census and aggregated to the neighborhood level. Data for total population, number of households, and race and ethnicity came from the block-level 2010 decennial census. Block group estimates for vehicle ownership and persons living in poverty were obtained from the American Community Survey (ACS) 5-year estimates (2011 – 2015). Neighborhood boundaries were obtained from the City of Baltimore.

## Data Preparation

### Bicycle Network

The LTS dataset was a static, visual representation of the street network. To generate service areas, the network was edited for more realistic bicycle route calculation. Select vertices were manually removed so that bridges would not connect to streets below, and limited access highways and ramps were removed. These adjustment partially mitigated the lack of elevation data. The off-street trails were connected to the edited LTS network and designated LTS 1. The final network was then built with the ArcGIS Network Analyst tool, with LTS 3 and 4 incorporated as restrictions that can be turned on or off. These restrictions were tested by running the Network Analyst route tool in areas with high-stress barriers and ensuring that logical routes were produced. Network preparation is further detailed in Appendix A.

Only projects listed as physically separated facilities (cycle tracks or protected bike lanes), wide bike lanes, buffered bike lanes, and bike boulevards were retained in the final list; sharrow projects were removed because they are not sufficient for reducing LTS. Some projects that were broken into multiple segments were merged to reduce the number of extremely short projects. Reclassifying the LTS after the installation of a new facility may require more nuanced knowledge of which criteria resulted in the original LTS classification. For the purposes of this analysis, it was assumed that all projects would bring the comfort level of the street to LTS 1.[1]

The recommended project layer appeared to be a mix of features copied from the street network and manually digitized features that did not align precisely with the underlying street network. These inconsistences were mitigated by adding more vertices and then snapping the project segments to align with the street network until a sufficient number of links from the underlying street network shared a line segment with the recommended project features, but results must be interpreted with caution. See Appendix A for details.

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[1] LTS 1 may not be achievable in all cases, and in future analyses it could be desirable to assess accessibility for LTS 1 and 2 separately when considering young and elderly riders

## Business Data

Businesses were selected by using the 6-digit NAICS code and then scanning the names of the businesses to identify the final two digits. Public libraries and pharmacies were extracted simply using the NAICS-based code, as shown in Table 1. Banks were extracted using the six-digit NAICS code with the condition of having at least 1 employee to avoid ATMs. Supermarkets were a subset of grocery stores in the ESRI data and not readily identifiable. Grengs (2015) isolated supermarkets by using grocery stores of at least 45,000 square feet; following this example, stores over 40,000 square feet (the highest square footage in the data) were selected. The data did not contain any locations that were 10,000 to 39,999 square feet, but there were several Safeway locations and discount supermarkets like Save-A-Lot, Food King, and Aldi with square footage of less than 9,999. Therefore smaller grocery stores that nonetheless had over 50 employees were included as supermarkets. Gourmet grocery stores were removed from this latter set. Prior to generating service areas, businesses that appeared to be closed or miscategorized, such as pharmaceutical companies, were removed.

**Table 1. Business Data Selection**

| Business Type | NAICS-Based code | Additional Criteria | Final Number |
|---|---|---|---|
| Bank | 522110* | Number of employees > 0 | 147 |
| Pharmacy | 44611009 | N/A | 146 |
| Public Library | 51912006 | N/A | 39 |
| Supermarket | 44511003 | Square feet > 40,000;<br>OR Square feet = 2,500 – 9,999 AND Number of employees > 50 | 22 |

The final set of business locations is shown in Figure 5.

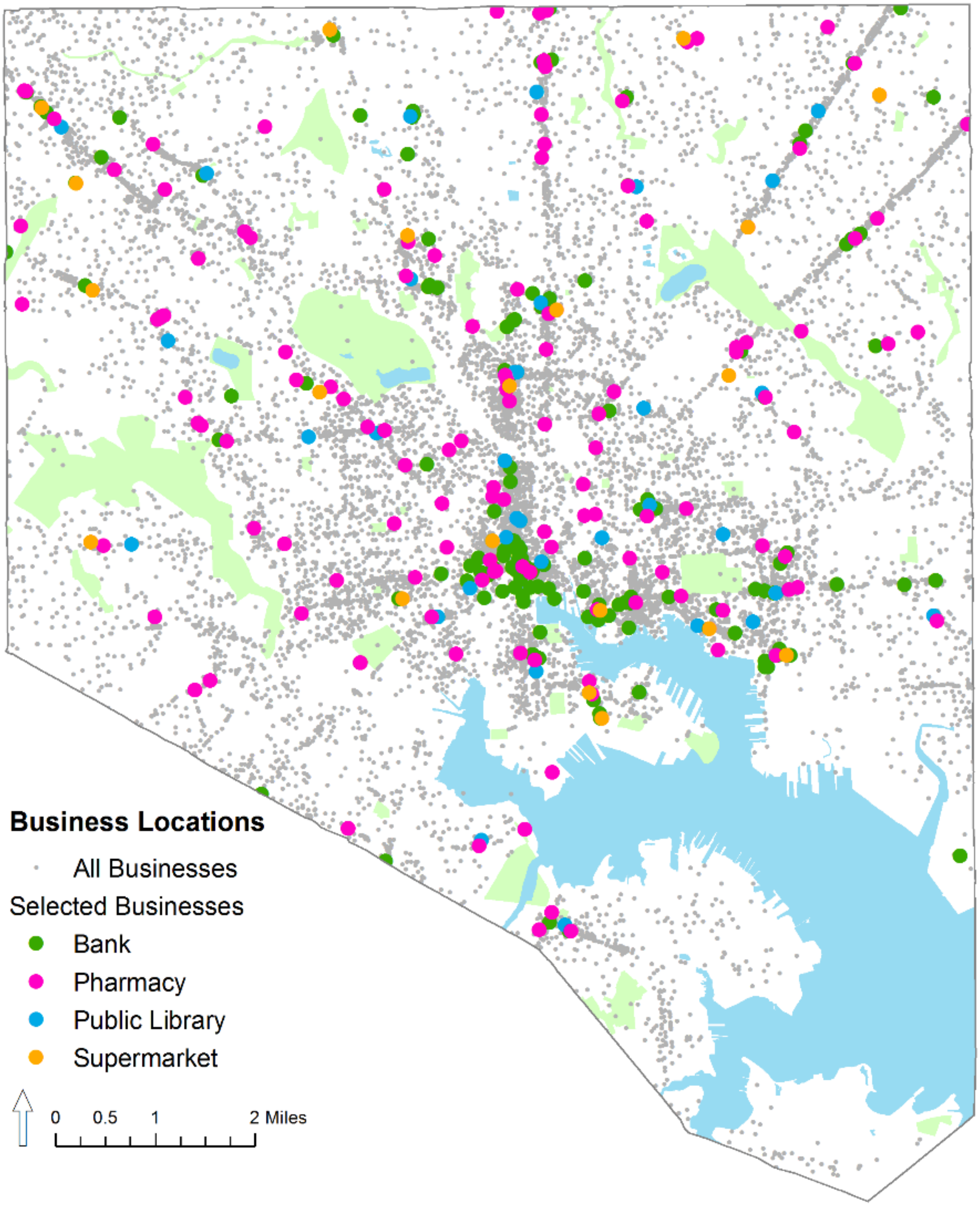


**Figure 5. Business Locations**

## Demographic Data

To generate service areas containing demographic attributes for neighborhood, census data at different geographic scales were aggregated to the neighborhood level and associated with the neighborhood centroid. Since population, race, and ethnicity data are available at the finest scale of census blocks, but poverty and vehicle ownership status is only available for census block groups, the block-group share of persons in poverty and households with no vehicle available was applied to the block-level population and household counts for each block. The population counts for each block centroid within a neighborhood boundary was then summed to the neighborhood level. The result was a count of people and households for each demographic group of interest for each neighborhood. City-wide distributions are shown in Table 2.

**Table 2. City of Baltimore Demographics**

| Total Pop. | Black | Non-Hispanic White | Hispanic | Asian and Other | Persons in Poverty | Not in Poverty | Total House-holds | Zero-Vehicle House-holds | House-holds with Vehicles |
|---|---|---|---|---|---|---|---|---|---|
| 620,723 | 392,898 | 173,945 | 25,949 | 27,931 | 146,005 | 474,718 | 296,519 | 91,979 | 204,540 |
| | 63% | 28% | 4% | 4% | 24% | 76% | | 31% | 69% |

Baltimore is a highly segregated city as a result of racial discrimination and the historical practice of redlining (Pietila, 2010). The lingering legacy of racist practices in the real estate and financial lending sectors is clear from the current-day neighborhood composition, with many neighborhoods being home to a population that is over 90% African American. Figure 6 and Figure 7 show that high-poverty neighborhoods are predominantly home to black and Hispanic residents, while Asians tend to be more concentrated in in the same areas as white residents. Though issues of equity and justice in Baltimore have typically focused on black communities in relation to whites, East Baltimore's growing Hispanic population has been found to suffer from health disparities and lack of access to healthcare (Anft, 2016). The industrial nature of East Baltimore may also limit opportunities for physical activity. As suggested by Figure 6, the notion of the "White L" is somewhat of a simplification.

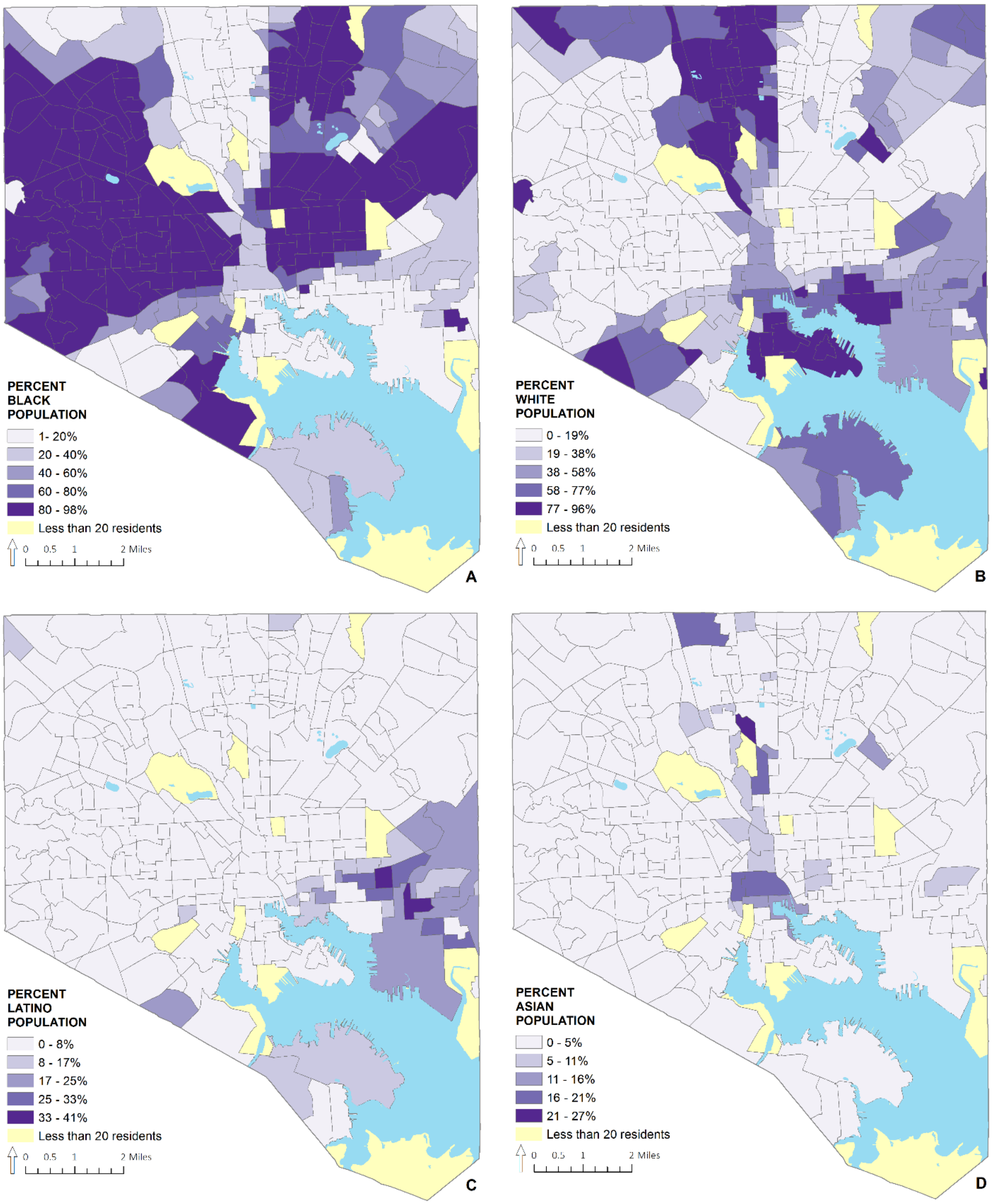


**Figure 6. Baltimore Neighborhood Demographics: Racial/Ethnic Distributions**

The distribution of poverty largely aligns with the distribution of populations of color. Likewise, zero-vehicle households tend to be located in the same neighborhoods as low-income households, as shown in Figure 7 and Figure 8.

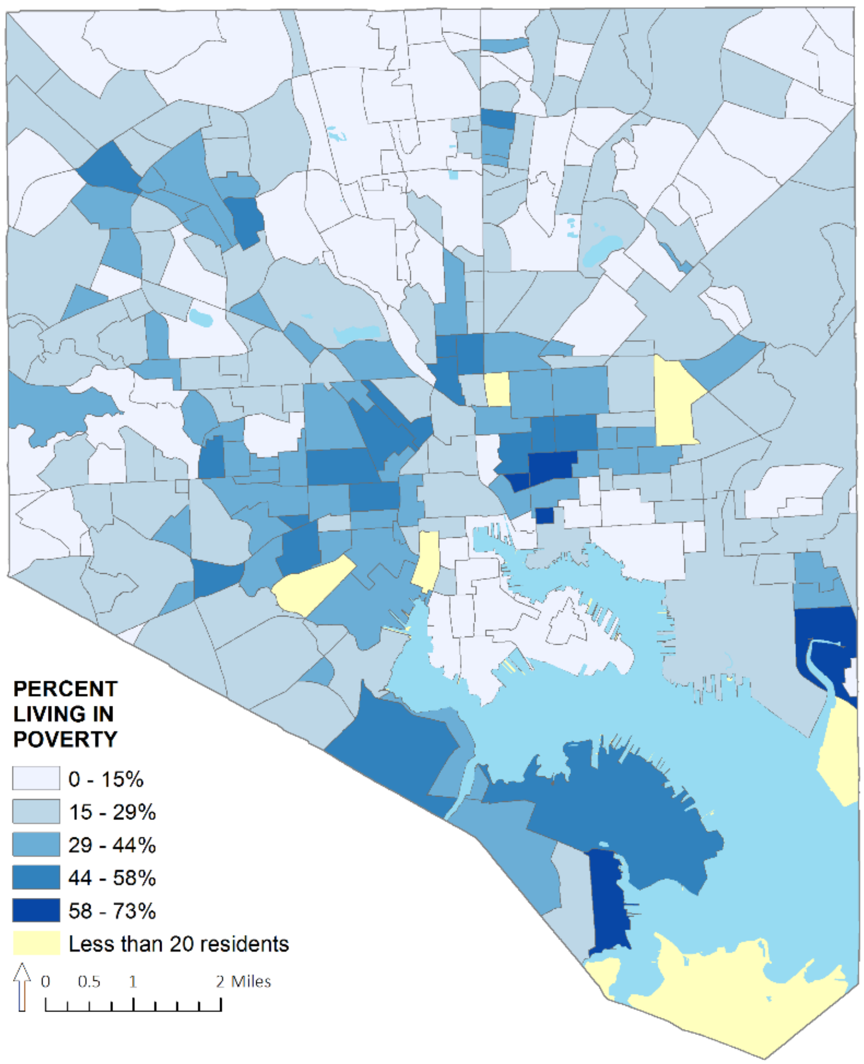


**Figure 7. Baltimore Neighborhood Demographics: Poverty Rate**

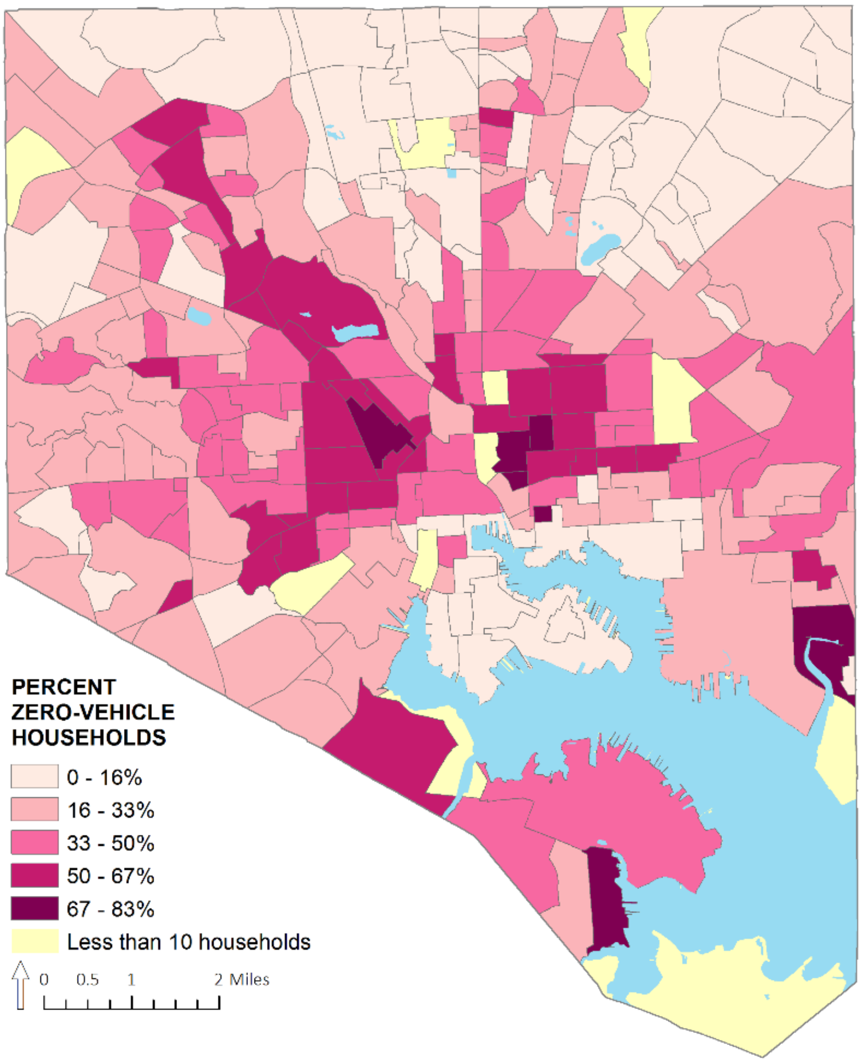


**Figure 8. Baltimore Neighborhood Demographics: Zero-Vehicle Households**

# Data Analysis

## Accessibility Performance Measures

Accessibility using the low-stress bicycle network was quantified using six performance measures (PM) calculated for each neighborhood,[2] as shown in Table 3.

[2] Out of 278 neighborhoods, 14 had centroids that were trapped by high-stress streets on all sides and therefore had no service area and performance measures of zero in the baseline analysis. An additional 23 neighborhood centroids were located closest to a high-stress street and therefore unable to access nearby low-stress streets. For these cases, the neighborhood centroids were moved an average of 140 feet to allow a service area to be created. See Appendix A for a listing a neighborhoods centroids that were manually adjusted.

**Table 3. Performance Measures**

| # | Name | Description |
|---|---|---|
| 1 | Area | Size of service area (square miles) |
| 2 | Distance | Low-stress network distance within service area (miles) |
| 3 | Business Total | Total number of accessible businesses |
| 4 | Business Diversity | At least one supermarket, pharmacy, bank, and library is accessible (yes/no) |
| 5 | Supermarket Access | At least one supermarket is accessible (yes/no) |
| 6 | Library Access | At least one library is accessible (yes/no) |

Performance measures 1 and 2 are space-based measures that do not require data other than the street network and neighborhood centroids. Performance measures 3 through 6 are place-based measures that change based on the input data, holding PM 1 and 2 constant.

Service areas calculated in ArcMap include polygon area and accessible street network distance. Network distance is a function of both the area and the urban form, with densely gridded streets increasing the distance for equally sized service areas compared to low-density urban form. The distance measure for the automobile accessible areas includes all streets (LTS 1 through 4) while the distance measure for low-stress bicycle accessible areas includes only LTS 1 and LTS 2 streets. The distance for automobiles is an underestimate, since limited access roadways were removed from the dataset.

Business point data were spatially joined to the service areas to obtain the number and types of businesses accessible to each neighborhood within a two-mile, low-stress bicycle ride. The business-based performance measures reflect land use and local economic conditions in addition to the quality of the bicycle network in allowing or hindering access to business destinations. It was expected that centrally-located service areas would score higher on the Business Total and Diversity measures due to the density and diversity of urban land uses. The Supermarket Access measure was selected because of the necessity of food and because, as Grengs notes, "for certain kinds of trip purposes—most notably in travel to supermarkets—vulnerable social groups appear to be systematically disadvantaged" (2015). The Library Access measure was selected because public libraries can site branch locations to serve local communities instead of for profit reasons. The City of Baltimore's Enoch Pratt Free Library system has 23 branches across the city; a few university libraries are also in the dataset. The distribution of libraries in Baltimore is more even, so bicycle accessibility to libraries is expected to be more dependent on LTS than on land use or distance to the central business district (CBD). By providing computers and internet, libraries can function as community resource centers that open up additional opportunities to jobs and other activities.

## Demographic and Equity Analysis

The demographic analysis identifies accessibility disparities between disadvantaged and not disadvantaged population groups. Conventional transportation equity or environmental justice analyses tend to first identify geographic areas containing a proportion of minority or low-income populations above a certain threshold and then analyze these areas for disproportionality with a reference group. However, this approach can miss areas that are just below a proportion threshold but still contain a large population of a particular demographic group. Thresholds favor demographic concentration, which could be useful in segregated areas, but at the expense of examining impacts to more dispersed, but nonetheless affected populations (Brodie & Amekudzi-Kennedy, 2016; Rowangould, Karner, & London, 2016). Instead, this research first assesses baseline performance for all neighborhoods in Baltimore, and then evaluates the demographic distribution of outcomes for equity. In this method, no thresholds are set for neighborhoods; rather, the number and proportion of members of a demographic group experiencing different levels of accessibility anywhere in the city are compared for each accessibility performance measure. The method is similar to one tested by Brodie and Amekudzi-Kennedy (2016) and used by Puget Sound Regional Council (2012).

For the demographic analysis, the total population and total number of households served as the reference groups for residents living in poverty and zero-vehicle households, respectively. The total population and white population served as the reference groups for black and Hispanic populations. Other persons of color were not included in the analysis because their counts were either very small, or in the case of Asians, they tended to live in the same areas as white residents. To compare across demographic groups, continuous data for performance measures 1, 2, and 3 were grouped into quartiles representing low, medium, high, and very high accessibility. The number of members in each demographic group experiencing each level of accessibility was summed across the entire demographic group, citywide. Though performance measures 4, 5, and 6 were binary accessibilities (access/no access), 5 and 6 were compared across demographic groups using the number of accessible supermarkets and libraries instead of whether or not at least one was accessible to better understand whether certain groups had access to more options. The process for incorporating demographic considerations into project prioritization is described in the next section.

## Project Prioritization

The accessibility gains created by each recommended project were quantified using an automated, iterative process in which service areas were generated for every neighborhood after reducing the LTS classifications on project links, one project at a time. Other studies have tended to evaluate the effect of full plan buildout instead of analyzing each project separately (e.g. Lowry et al., 2016 and McNeil, 2011). Though Lowry et al. (2016) do provide rankings for individual projects based on a single metric, they note that analyzing individual projects would not capture the interaction among projects. However, there are several reasons why what they call “piecemeal analysis” is useful. First, interaction effects do not start immediately due to construction phasing, and phasing should align with prioritization results where possible. Second, the question of who experiences what type of accessibility gain can be better answered by examining the impacts of specific projects on specific neighborhoods. The affected neighborhoods are not chosen in advance; instead, running every neighborhood service area for every project, though data-intensive, allows neighborhood-level accessibility results to emerge from the data. Third, linking individual projects to specific benefits, such as increased access to a currently only auto-accessible supermarket allows planners and community members to better identify tradeoffs and priorities.

Each project was isolated using its ID number, the underlying street links—both the project corridor and all crossing links—were temporarily classified as LTS 1. Service areas were generated for all neighborhoods and spatially joined to businesses. The street links were then reverted to their original LTS, and the process was repeated for the next project, resulting in 106 output files containing the area, network distance, and numbers and types of businesses accessible to each neighborhood as a result of that project. Though it was expected that most projects would not affect neighborhoods on the other side of the city, the citywide iteration allows for detection of unanticipated effects.

There were 27,984 project-neighborhood combinations (106 projects and 264 neighborhoods[3]). The difference between the baseline and the project result was taken for each performance measure as well as for the number of each accessible business type. Most projects did not affect neighborhoods that were far away, or nearby neighborhoods that did not have large enough service areas to reach the project. After removing all of the project-neighborhood combinations that showed no change in any accessibility measures, there were 3,888 combinations. However, these included projects that caused insignificant changes in service area and distance. At a 0.01 square mile service area increase and a 0.12 mi street distance increase, new businesses start to become accessible. To be conservative, a threshold of +0.019 square miles or +0.1 miles was set; any project-neighborhood combination not meeting either of these was eliminated, resulting in a final set of 1,986 combinations.

Project-neighborhood combinations were then grouped by project ID and summed over each performance measure and over demographic counts to quantify the cumulative impact of each project across all affected neighborhoods. For example, Project 86 (one segment of Harford Road with a planned separated facility) would affect accessibility for eleven neighborhoods, as shown in Table 4.

**Table 4. Accessibility Gains for Each Affected Neighborhood due to a Single Project**

| ` | **Project ID** | **PM 1:** Area Increase (sq. mi) | **PM 2:** Street Distance Increase (mi) | **PM 3:** Total Business Increase | **PM 4:** New Access to all 4 business types | **PM 5:** New Access to a Super-market | **PM 6:** New Access to a Library |
|---|---|---|---|---|---|---|---|
| Arcadia | 86 | 0.79 | 19.31 | 1 | 0 | 0 | 1 |
| Belair-Edison | | 0.07 | 2.27 | 0 | 0 | 0 | 0 |
| Belair-Parkside | | 0.71 | 17.44 | 1 | 1 | 0 | 1 |
| Beverly Hills | | 0.94 | 22.15 | 1 | 0 | 0 | 1 |
| Lauraville | | 1.03 | 31.93 | 2 | 0 | 1 | 0 |
| Lower Herring Run Park | | 0.08 | 2.51 | 0 | 0 | 0 | 0 |
| Moravia-Walther | | 0.88 | 20.08 | 1 | 0 | 0 | 1 |
| Morgan Park | | 0.73 | 22.79 | 2 | 0 | 1 | 0 |
| Morgan State University | | 0.7 | 21.76 | 2 | 0 | 1 | 0 |
| Parkside | | 0.11 | 3.28 | 2 | 0 | 1 | 0 |
| Waltherson | | 0.45 | 12.92 | 0 | 0 | 0 | 0 |
| **Cumulative Impact to 11 Neighborhoods** | | **6.49** | **176.44** | **12** | **1** | **4** | **4** |

[3] None of the 106 projects affected the fourteen neighborhoods that had no baseline service area. Therefore, impact was assessed for only 264 out of 278 neighborhoods. Projects were recommended primarily for commercial and residential areas, not industrial areas where the fourteen neighborhoods tended to be located.

The performance measures are summed across all neighborhoods to arrive at cumulative impact, to be used for comparative purposes and for project ranking.[4] Whereas for the baseline, the performance measures are at the neighborhood level, for the prioritization, the measures are at the project level. This process was repeated for every project, and a similar process was used for demographic data, as shown in the example for Project 86 (Table 5).

**Table 5. Demographic Impact by Neighborhood due to a Single Project**

| Neighborhood | ID | Total Pop. | Persons of Color | Black | White | Living in Poverty | Total House-holds | Zero-Vehicle House-holds |
|---|---|---|---|---|---|---|---|---|
| Arcadia | | 16,690 | 15,383 | 14,889 | 1,307 | 4,069 | 6,710 | 2,028 |
| Belair-Edison | | 444 | 338 | 297 | 106 | 181 | 183 | 41 |
| Belair-Parkside | | 669 | 288 | 264 | 381 | 66 | 317 | 43 |
| Beverly Hills | | 4,151 | 2,499 | 2,204 | 1,652 | 465 | 1,703 | 109 |
| Lauraville | | 200 | 191 | 189 | 9 | 20 | 80 | 9 |
| Lower Herring Run Park | | 999 | 633 | 580 | 366 | 89 | 432 | 48 |
| Moravia-Walther | | 256 | 253 | 243 | 3 | 18 | 121 | 5 |
| Morgan Park | 86 | 1,790 | 1,742 | 1,694 | 48 | 292 | 37 | 6 |
| Morgan State University | | 2,683 | 2,404 | 2,220 | 279 | 366 | 1,190 | 321 |
| Parkside | | 6,980 | 5,045 | 4,656 | 1,935 | 565 | 2,953 | 441 |
| Waltherson | | 16,690 | 15,383 | 14,889 | 1,307 | 4,069 | 6,710 | 2,028 |
| **Cumulative Demographic Impact Across 11 Neighbor-hoods** | | **36,097** | **29,402** | **27,771** | **6,695** | **6,417** | **14,236** | **3,131** |
| | | | **81%** | **77%** | **19%** | **19%** | **18%** | **22%** |

The cumulative demographic impact represents an optimistic, theoretical value for the total number of people who would benefit from a particular project. In reality, a small proportion of the affected population would travel by bicycle. Also, this method is based on the neighborhood centroid, which lets a single point represent an entire group of residents that may be distributed unevenly throughout the neighborhood, with some closer and others further from the project location. However, having been applied citywide, the cumulative measure allows for comparison relative to other projects. The final step of the prioritization was to rank projects by each of the cumulative results. The cumulative impacts could

[4] As can be seen, four neighborhoods gained access to at least one supermarket when previously having no access. It is likely the same supermarket for all four neighborhoods, so the cumulative impact of four does not mean that four supermarkets are now accessible; it means that Project 86 increased access for 4 neighborhoods. Likewise, the business total of 12 indicates that overall, the project increased access for a majority of the 11 neighborhoods, but the businesses that are now accessible likely overlap.

have been combined into a single index, but purpose of this analysis is to differentiate between different accessibility and equity impacts.

After calculating cumulative accessibility gains and demographic impacts, the projects were ranked by each performance measure and by population group. Performance measures 1, 2, and 3 were normalized by project length for an additional ranking (1N, 2N, and 3N), as shown in Table 6. Both the normalized and non-normalized versions are retained to identify projects that rank highly for both.

**Table 6. Project Rankings by Performance Measure**

| # | Name | Rankings based on: |
|---|---|---|
| 1 | Area | Cumulative increase (1) + Increase normalized by project length (1N) |
| 2 | Distance | Cumulative increase (2) + Increase normalized by project length (2N) |
| 3 | Business Total | Cumulative increase (3) + Increase normalized by project length (3N) |
| 4 | Business Diversity | Number of neighborhoods with new access to all four types |
| 5 | Food Access | Number of neighborhoods with new access to a supermarket |
| 6 | Library Access | Number of neighborhoods with new access to a library |

For demographic criteria, projects were ranked according to the percentage of all residents or households affected by a particular project who are black, Hispanic, living in poverty, or have no vehicle. They were also ranked by percentage of white residents for comparison.

# RESULTS

Baseline results for the existing network are examined first; prioritization results are shared next.

## Baseline Results

This section examines the spatial, quantitative, and demographic distributions for each of the six performance measures.

### Service Area Size and Accessible Street Distance

As shown in Table 7, the maximum low-stress bicycle service area for a neighborhood, at 5 square miles, is only 56% as large as that of the maximum auto service area. A person biking in an average low-stress area of just over 2 square miles can cover only 36% of the same area as a driver. Neighborhoods with minimal access to low-stress streets are affected the most: 14 neighborhoods had no bicycle service area at all due to high-stress streets, and the smallest auto service area of less than a square mile represents an increase of over 4,000% over the smallest bicycle service area of 0.02 square miles. Likewise, accessible street distance for bicycles ranged from 1% to 57% of the available street distance for motor vehicles. Since the no-restriction network was missing all highways, the auto accessibility results are conservative.

**Table 7. Descriptive Statistics for Performance Measures 1 and 2**

| | PM 1: Area (square miles) | | PM 2: Distance (miles) | |
|---|---|---|---|---|
| | Bicycle (LTS 1 and 2) | Auto (LTS 1 - 4) | Bicycle (LTS 1 and 2) | Auto (LTS 1 - 4) |
| Minimum | 0.02 | 0.91 | 0.15 | 15.20 |
| Maximum | 5.00 | 8.86 | 217.70 | 380.20 |
| Mean | 2.16 | 6.04 | 81.91 | 207.60 |
| Standard Deviation | 1.27 | 1.80 | 57.21 | 88.49 |

Note: This table does not contain bicycle results for fourteen neighborhoods whose centroids were blocked from entering the LTS 1 and 2 network; the auto results include all neighborhoods. The bicycle and auto results do not necessarily correspond to the same neighborhood.

The minimum service area is technically zero square miles, but the table does not include neighborhoods with no service areas. Including the fourteen service areas of zero would reduce the average bicycle service area to 2.05 square miles. Some of these neighborhoods with no service area contain no or few residents (Carroll Park, Dundalk Marine Terminal, Orangeville Industrial Area, and Hawkins Point, where a hazardous waste facility is located). However, some of these areas are home to hundreds of residents, for example, Locust Point Industrial Area and O'Donnell Heights, shown in Figure 9.

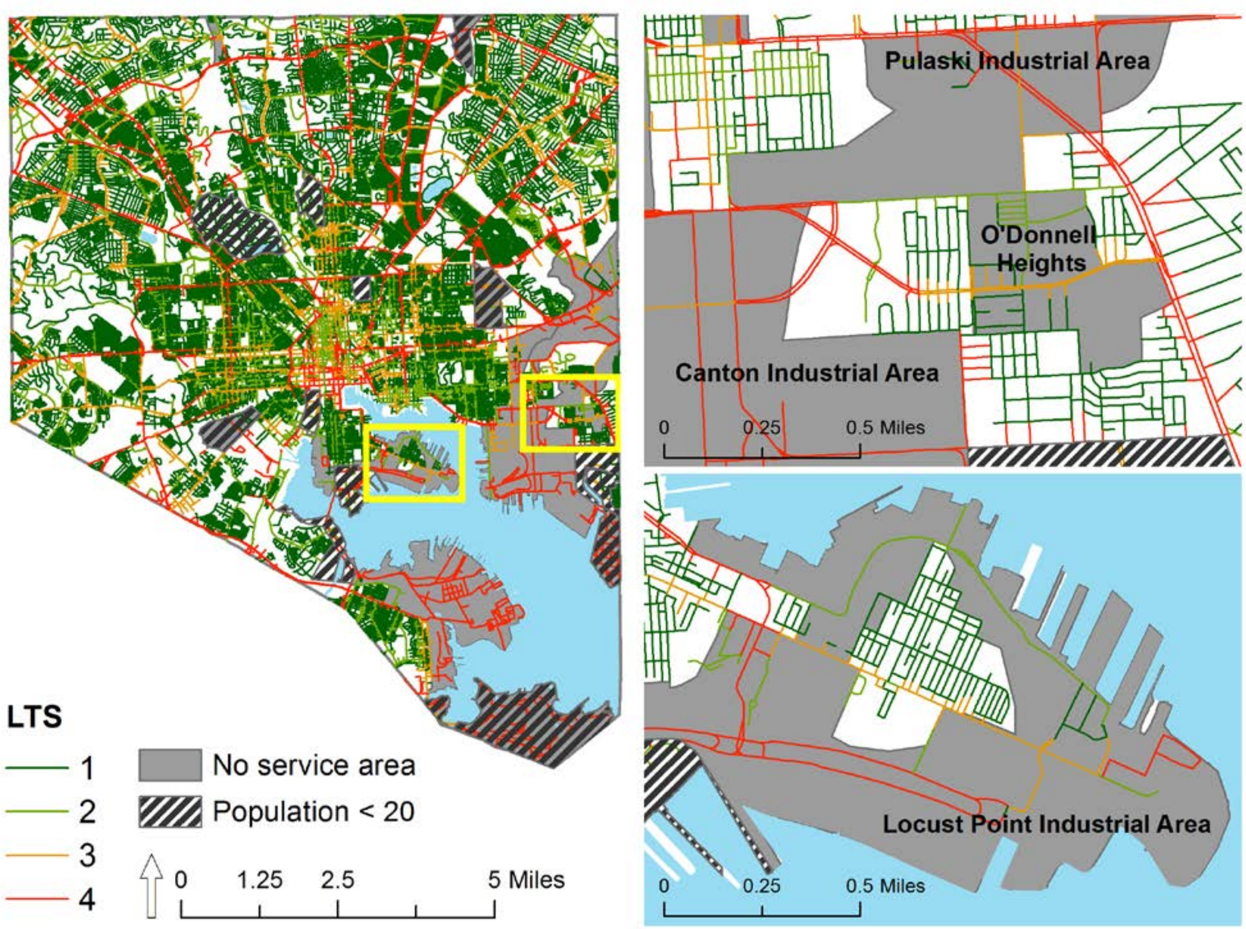


**Figure 9. Select Neighborhoods with No Service Area**

Locust Point Industrial Area has 583 residents, and it completely surrounds the neighborhood of Locust Point, which itself has over 2,000 residents and nearly 8 miles of gridded low-stress streets within its tiny service area. However, the predominantly white and higher-income neighborhood does not have low-stress connections to leave the peninsula. The largest neighborhood with no service area, O'Donnell Heights, is a former public housing site that is currently being redeveloped to have over 900 affordable units (Sherman, 2016). The 2010 population consisted of 289 households of which 54% did not have a vehicle. In total, neighborhoods with no service area contain 2,423 residents of which 53% are persons of color and 26% are below the poverty line, living in 1,302 households of which 29% do not have a vehicle.

Neighborhoods with larger service areas were more likely to be centrally located, as shown in Figure 10.

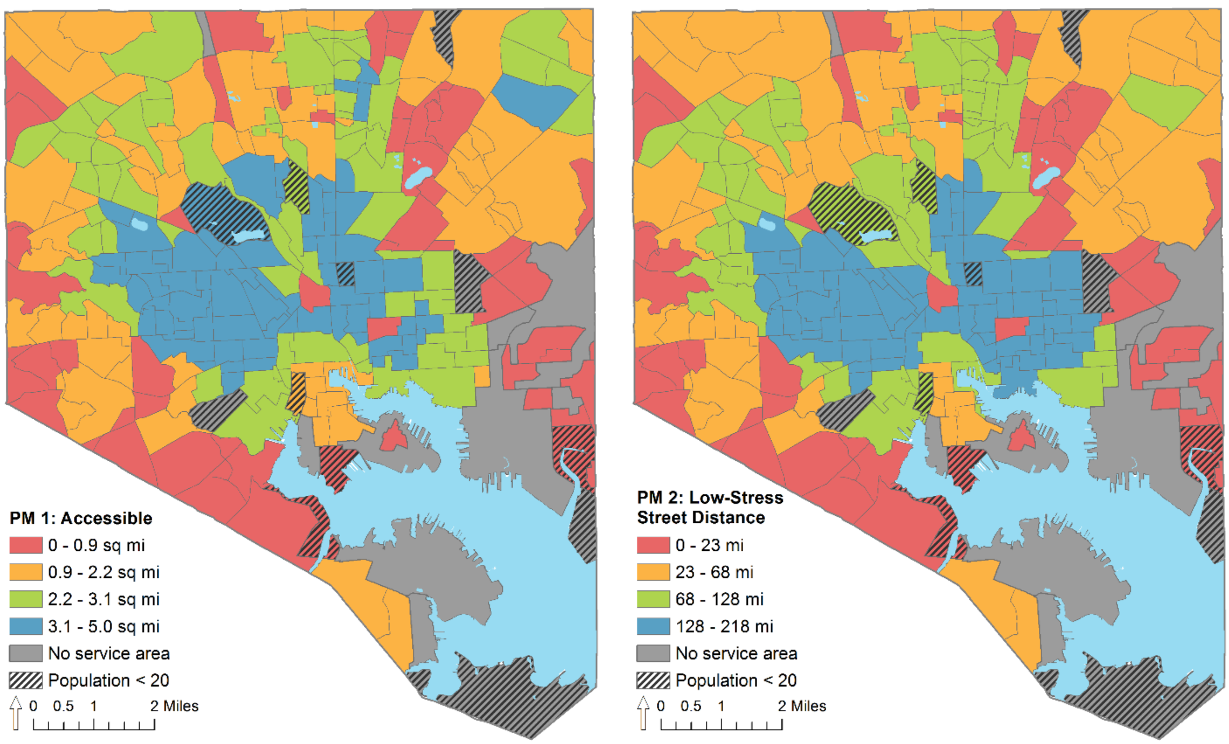


**Figure 10. Spatial Distribution of Accessible Area and Street Distance**

The service area size and distance results are likely due to a gridded street network with more signalized intersections and thus potential for low-stress connections through barriers. Large service areas extend far past neighborhood boundaries. Two extreme examples are Sandtown-Winchester in West Baltimore, and Butcher's Hill in Southeast Baltimore (Figure 11).

Of all neighborhoods, Sandtown-Winchester had the largest service area of 5 miles. This finding was unexpected, because the neighborhood is more infamously known for police shootings of civilians and vacant properties than bicycle infrastructure (Cassie, 2016). The service area result appears to be because of its dense grid of streets with lower speed limits and fewer lanes that were classified as LTS 1. Based on the LTS methodology, some high-stress streets like North Fulton Avenue act as barriers where there are unsignalized intersections such as Lorman Street, but signalized intersections such as Presstman Street allow the service area to cross the barrier. The service area thus expands far past where a visual assessment of high-stress barriers would place boundaries. Sandtown-Winchester's residents are 97% black with a 41% poverty rate; its results and similar ones from nearby neighborhoods may skew the accessibility results to appear more positive for majority-black and high-poverty neighborhoods.

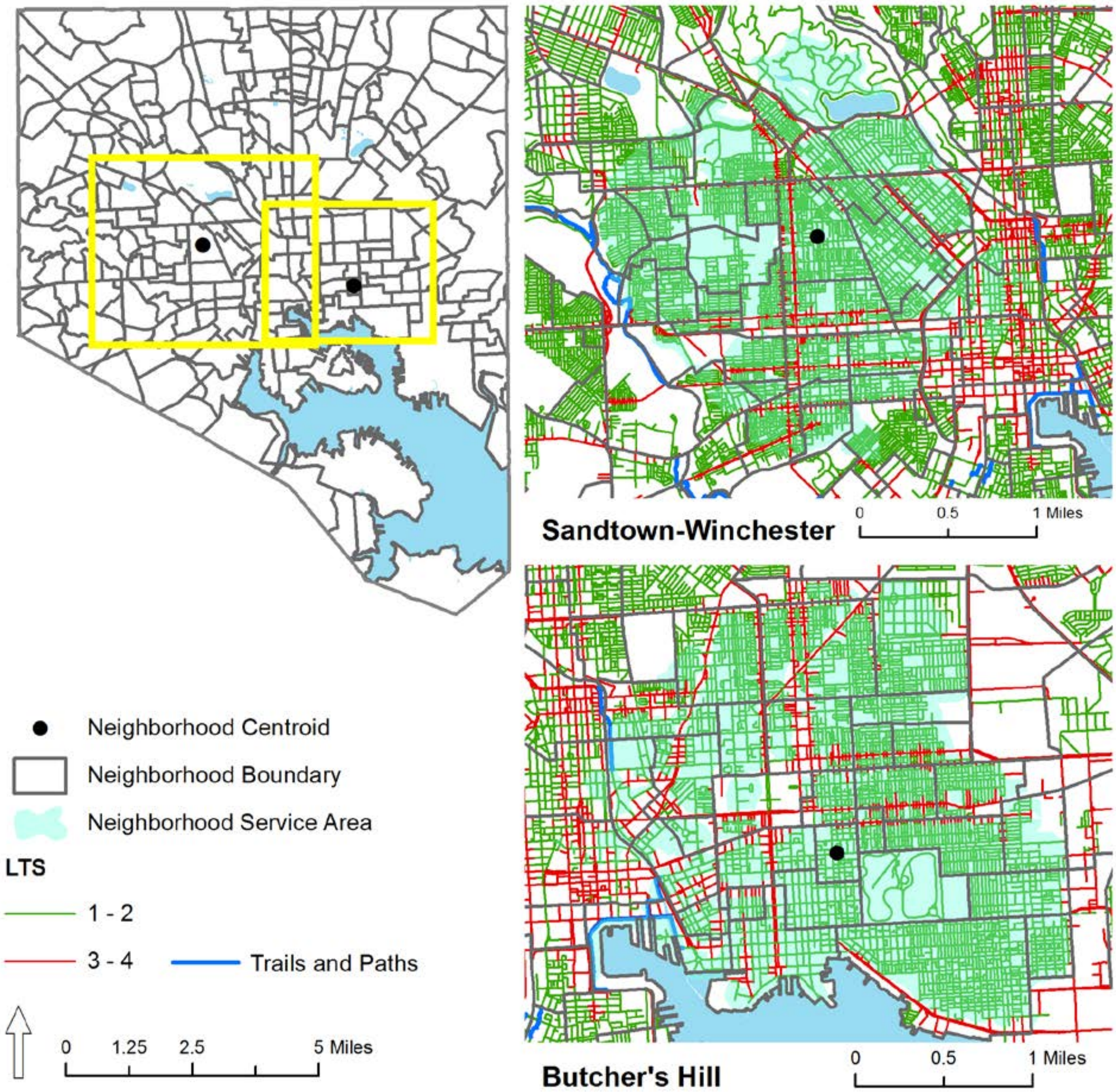


**Figure 11. Select Neighborhoods with Large Service Areas**

A similarly large service area originates from Butcher's Hill—a small neighborhood that recovered from the housing market crash and contains no vacancies (Willoughby, 2016). The 67% white neighborhood's 3.84 square mile service area, though only 26th-ranked out of 278 in terms of size, is 5th-ranked for miles of low-stress street distance and 2nd-ranked for total number of businesses. Both Sandtown-Winchester and Butcher's Hill illustrate that using what is assumed to be an accurate LTS network in terms of intersection classification yields service areas that appear to leak past barriers in a manner that may be technically correct, but is not likely to reflect actual cyclist behavior. Potential misclassification of intersection LTS could also lead to undesired leakage through high-stress barrier streets, creating larger-than-realistic service areas.

Two centrally-located neighborhoods that stand out as having small service areas are Mid-Town Belvedere, shown on the left side of Figure 12, and Dunbar-Broadway, shown on the right side. (Refer to Figure 10 for context). Dunbar-Broadway is the site of the John Hopkins Hospital complex, but it has a population of 889 residents, of which 95% are persons of color and over 60% are living in poverty with no vehicle. Mid-Town Belvedere contains cultural venues and restaurants and has a racially diverse population of over 3830 residents, with 30% of households having no vehicle. The high-stress barriers are evident in the lower half of the figure; they constrain the service areas to a fraction of the neighborhood. In the case of Dunbar-Broadway, moving the neighborhood origin would not have changed the result. However, an origin further south for Midtown-Belvedere could have allowed for a larger service area.

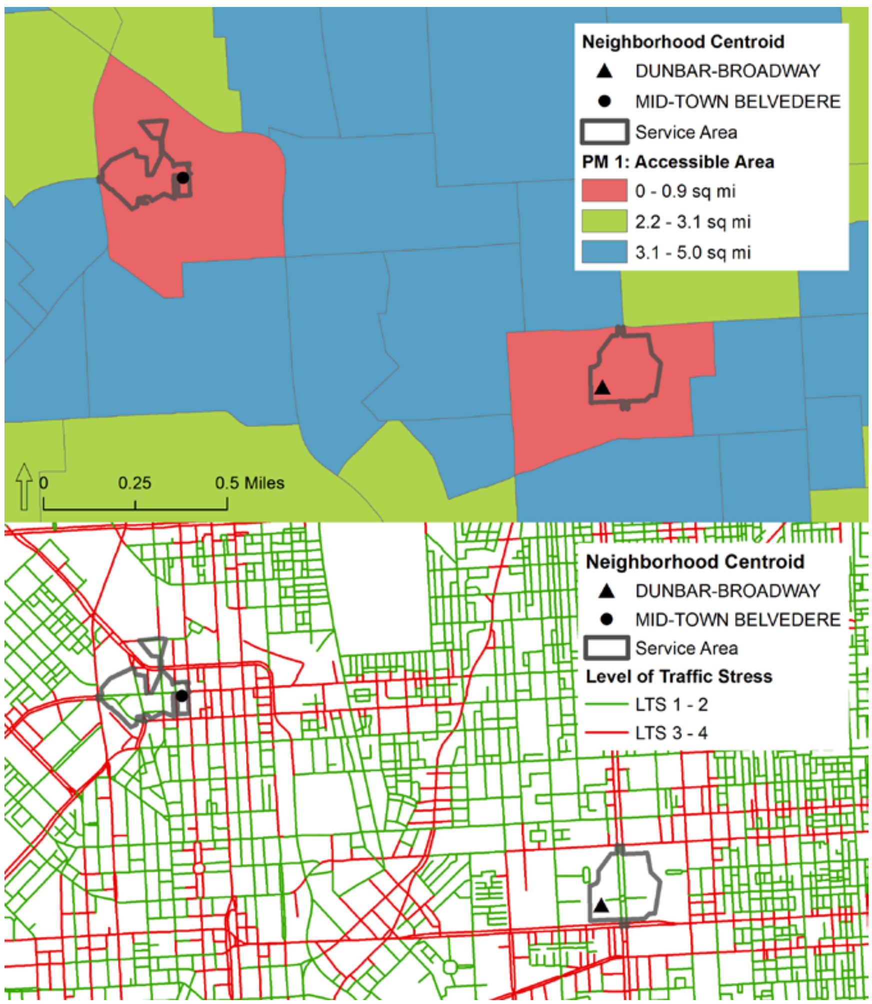


**Figure 12. Mid-Town Belvedere and Dunbar-Broadway Baseline Service Areas**

In general it appeared that service areas functioned well in terms of responding to major barriers. However, they are sensitive to the location of the neighborhood centroid, especially outside of the downtown grid. For example, neighborhood with the smallest service area and street distance was Blythewood, shown in Figure 13.

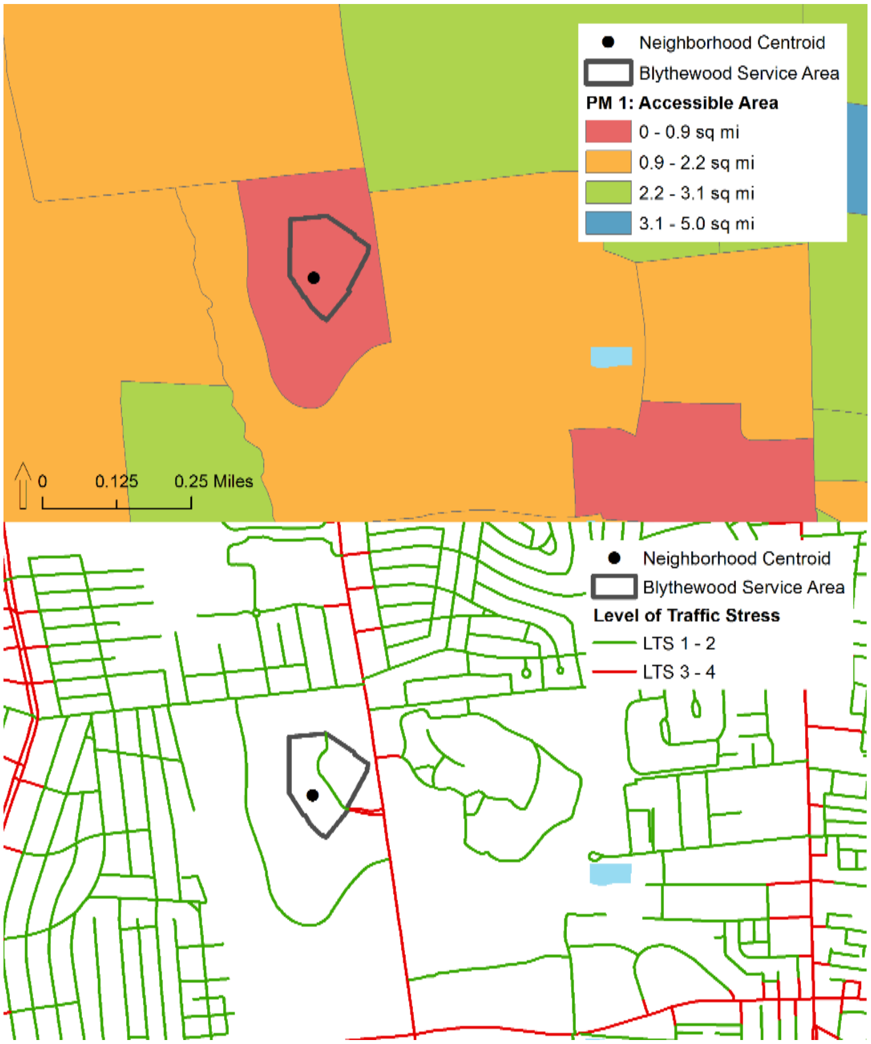


**Figure 13. Blythewood Baseline Service Area**

This 95% white, affluent neighborhood would have a similar service area as adjacent Roland Park (which had service area of 1.27 square miles) if the centroid were a bit further to the west. The ESRI ArcMap service area function was set to access the network from the closest road segment, resulting in the route starting on Loyola University Maryland's Fitness Center driveway and being blocked by North Charles Street instead of taking the back route out of the residential part of the neighborhood along Blythewood Road, which delineates the neighborhood's western and southern boundaries.

The service area size and street distance results were compared across demographic groups. Figure 14 shows the proportion of each demographic group, citywide, experiencing low, medium, high, and very high levels of accessibility as represented by Performance Measures 1 and 2. Results for service area size and accessible street distance have similar distributions. This finding suggests that variation in neighborhood street density and LTS that would cause two neighborhoods to have the same service area but different accessible street distances evens out over the entire demographic group.

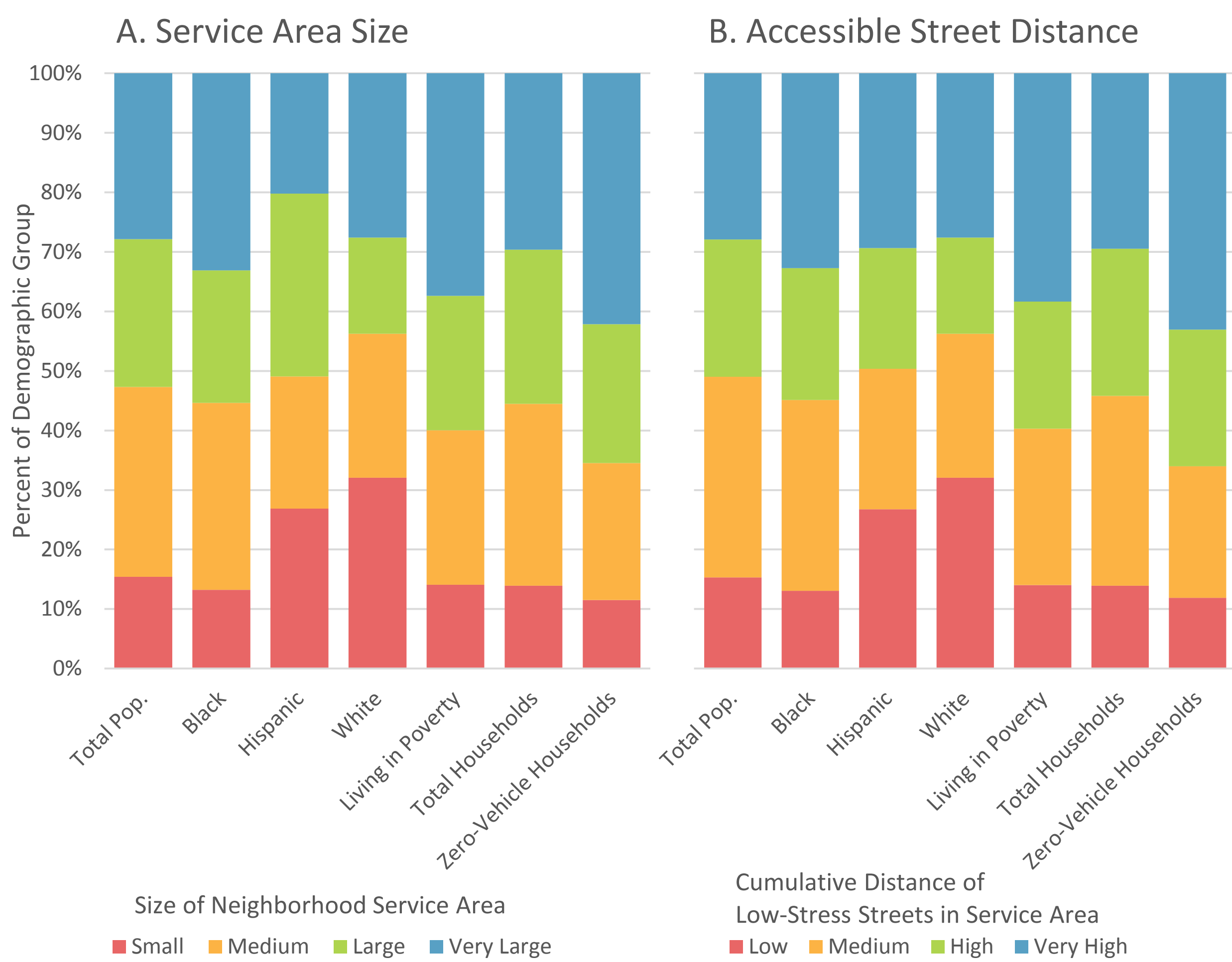


**Figure 14. Demographic Variation for Performance Measures 1 and 2**

Hispanic residents were most likely to live in neighborhoods with small or no service areas because of high-stress streets and industrial land uses; however, the gridded streets of some neighborhoods in East Baltimore increased the overall accessible street distance relative to results for white residents. Whites tended to have smaller service areas than black residents, likely because of suburban-style streets in areas of north central Baltimore and because of geographic constraints and interstate highway barriers in the South Baltimore peninsula. Results for majority-white neighborhoods at the city peripheries are skewed smaller, because the street network ends at the city boundary; in fact, real accessible areas would extend into Baltimore's suburbs. Black residents tended to have the largest service areas because of the dense grid of low-stress streets west and immediately east of downtown. It is important to note that the term "low-stress" refers only to street design and traffic conditions with regard to bicycling; racial profiling and racialized interactions between road users can make 'bicycling while black' stressful and even dangerous (Goddard, 2016). Likewise, lack of vehicle ownership among undocumented Hispanic communities paired with criminalization of immigrants can make a bicycle commuting a necessary yet stressful experience (Mirandé & Williams, 2016).

The distribution for zero-vehicle households may reflect the tendencies of these households to locate in walkeable areas with more transit. Taken alone, the distributions for Performance Measures 1 and 2 suggest that fewer equity gaps exist between black and white populations than expected. However, results for business accessibility are more mixed.

## Business Accessibility

As shown in Table 8, the average neighborhood in Baltimore lacks bicycle access to a supermarket, whereas pharmacies and banks are more accessible. Drivers are able to access nearly quadruple the average number of businesses and nearly triple the maximum number of businesses, compared to bicyclists.

**Table 8. Descriptive Statistics for Business Accessibility**

| | **Number of Accessible Businesses within Service Area** | | | | | | | | **PM 3: Business Total** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Supermarkets | | Pharmacies | | Banks | | Public Libraries | | | |
| | Bicycle | Auto | Bicycle | Auto | Bicycle | Auto | Bicycle | Auto | Bicycle | Auto |
| Minimum | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Maximum | 3 | 6 | 21 | 44 | 24 | 70 | 7 | 16 | 44 | 129 |
| Mean | 0.4 | 2.0 | 5 | 16 | 4 | 17 | 1 | 5 | 11 | 40 |
| Standard Deviation | 0.6 | 1.4 | 5.0 | 10.0 | 5.8 | 19.0 | 1.5 | 4.3 | 11.4 | 33.1 |

Figure 15 shows that 61 centrally-located neighborhoods can access over 18 businesses within 2 miles, while 76 neighborhoods have service areas that contain less than 2 businesses. The high business totals in the downtown are skewed by the banks in the financial district. A high number of accessible businesses does not guarantee diversity of types. As shown in the right side of Figure 15, only 68 neighborhoods could access at least one of each of the four business types. Whereas some neighborhoods with low to medium service area sizes had high business totals (or vice versa), nearly all of the neighborhoods with access to at least one of each business type also had large service areas.

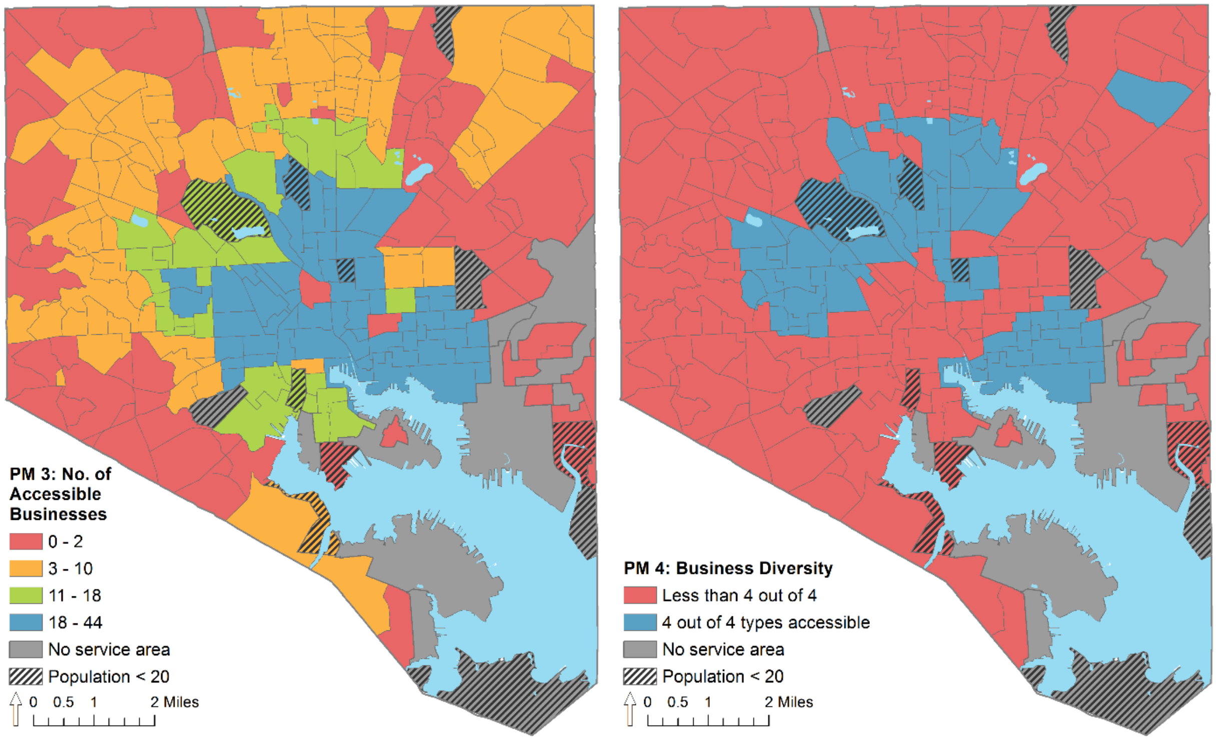


**Figure 15. Spatial Distributions of Number and Diversity of Accessible Businesses**

The distribution for level of business accessibility enjoyed by black and white residents was not extremely different from the citywide distribution, whereas Hispanic residents were more likely to have either high or low business accessibility (Figure 16a). White residents were more likely to have access to all four business types, while Hispanic residents were least likely to have diverse accessibility. Households living in poverty or without a vehicle were more likely to be located in areas with higher business accessibility. Still, over 170,000 residents live in neighborhoods with poor bicycle accessibility to these four business types. This result is owed partly to less mixed-use and commercial zoning in outlying areas of the city and partly to high-stress barriers to reaching businesses that are otherwise accessible by car. For some residents, living in a suburban-style, single-family home neighborhood is a choice, and bicycle accessibility to businesses may not be desired. However, other residents may desire or benefit from increased accessibility but lack the financial resources to move to areas with higher accessibility or the community power to attract new business development. These results do not shed light on the quality or affordability of accessible businesses.

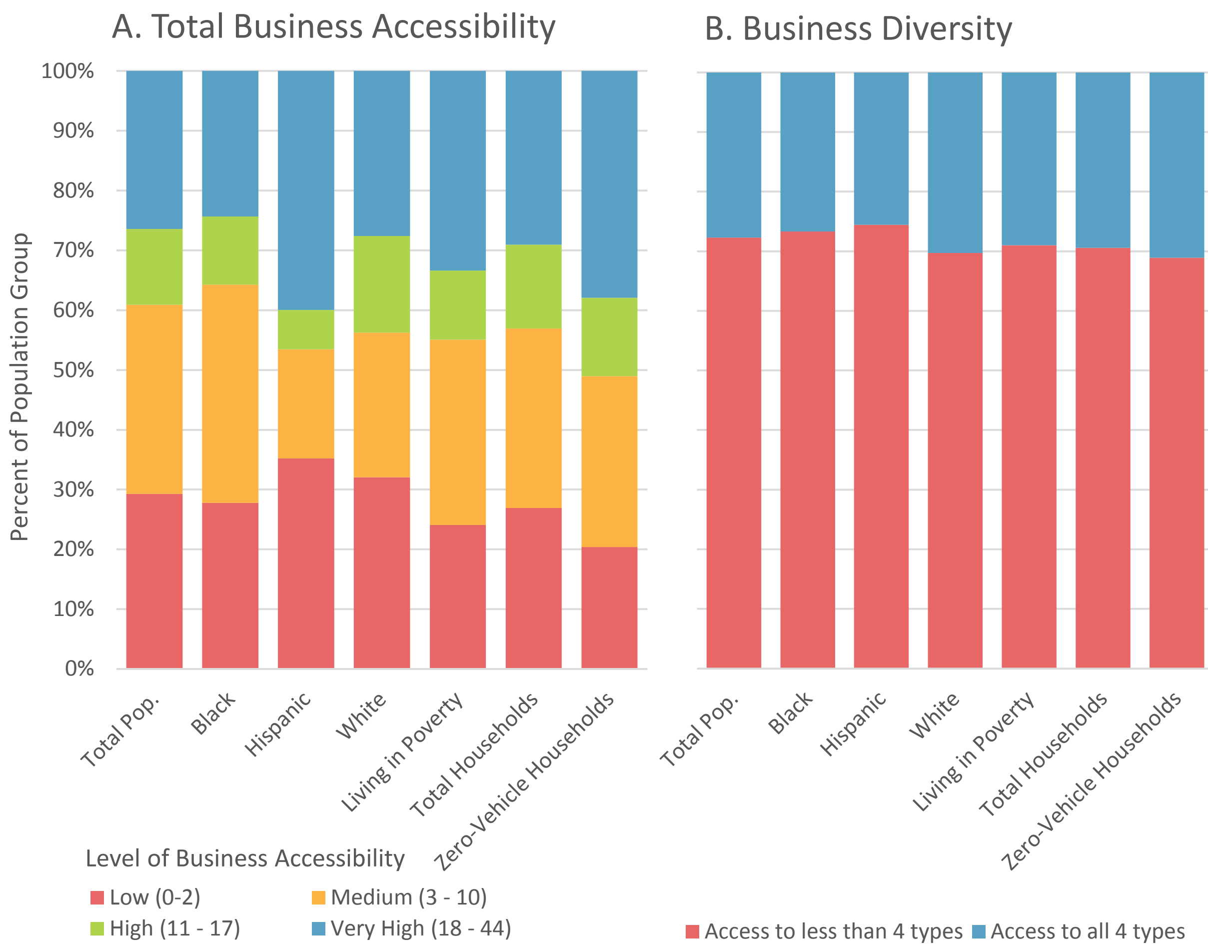


**Figure 16. Demographic Variation for Performance Measures 3 and 4**

The ability of residents to bike to at least one of each business type is largely limited by supermarket accessibility, as shown in Figure 17a.

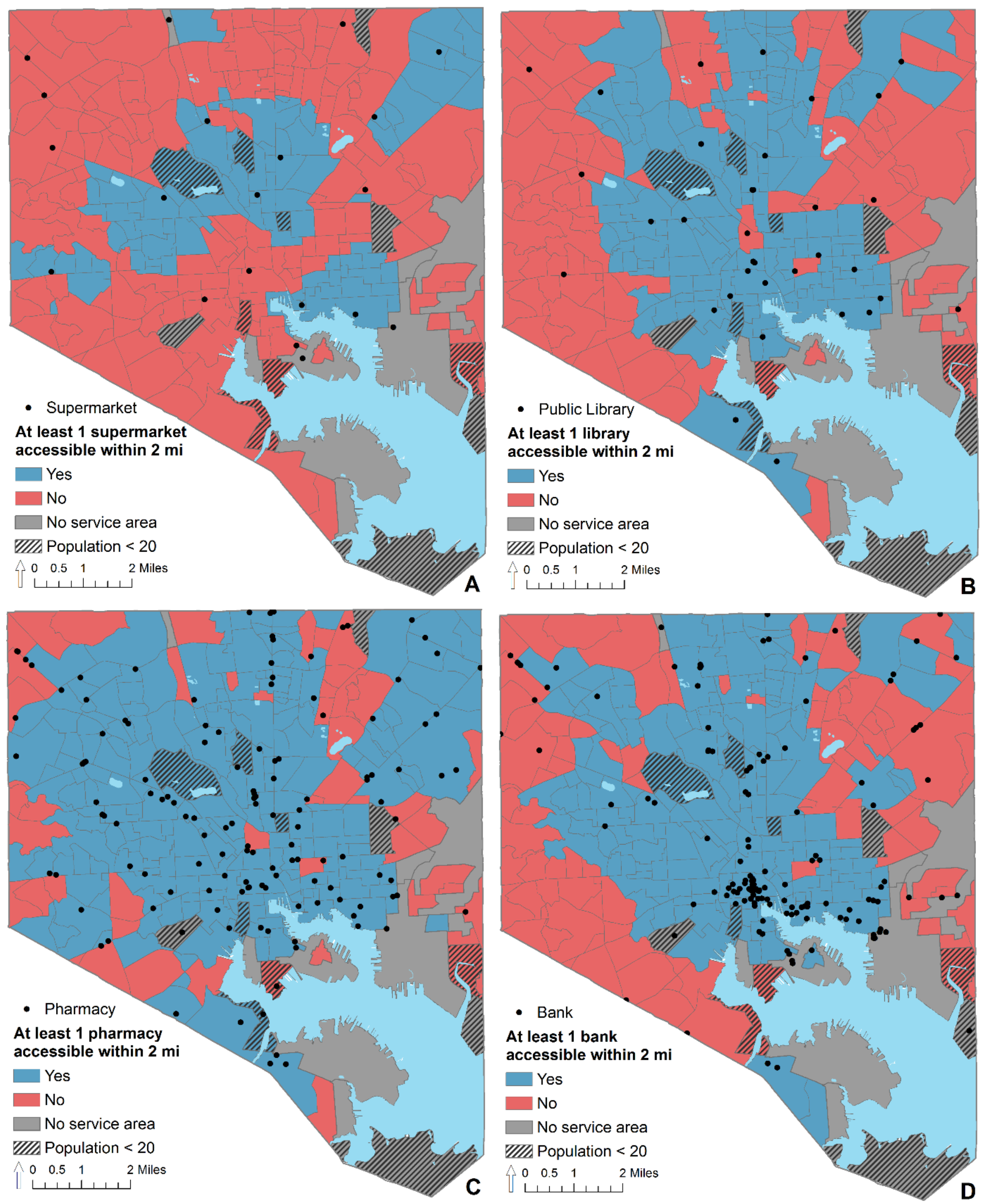


**Figure 17. Spatial Distributions of Accessibility to Each Business Type**

Figure 17d suggests that bank accessibility was overestimated for neighborhoods in West Baltimore, where there is a notable absence of bank locations, but large service areas caused banks to the north and to the east in downtown to be included in the PM 3 results.

Since supermarkets and libraries were the least numerous, accessibility to these destinations was assessed for each demographic group. As shown in Figure 18, the majority of residents, no matter their demographics, lack bicycle access to a single supermarket. A larger proportion of the population was more likely to have access to at least one public library, with low-income and zero-vehicle households having somewhat greater accessibility than other groups. White residents were more likely to have access to at least two or three supermarkets or up to seven libraries, despite tending to have smaller service areas and less accessible street distance. This result is likely due to business siting and could also be due to fewer high-stress barriers that would block access to nearby facilities, even within a small service area. Overall, it appears that black and Hispanic residents have roughly proportional access to at least one supermarket or library compared to white residents, but they have less options despite more access to low-stress streets.

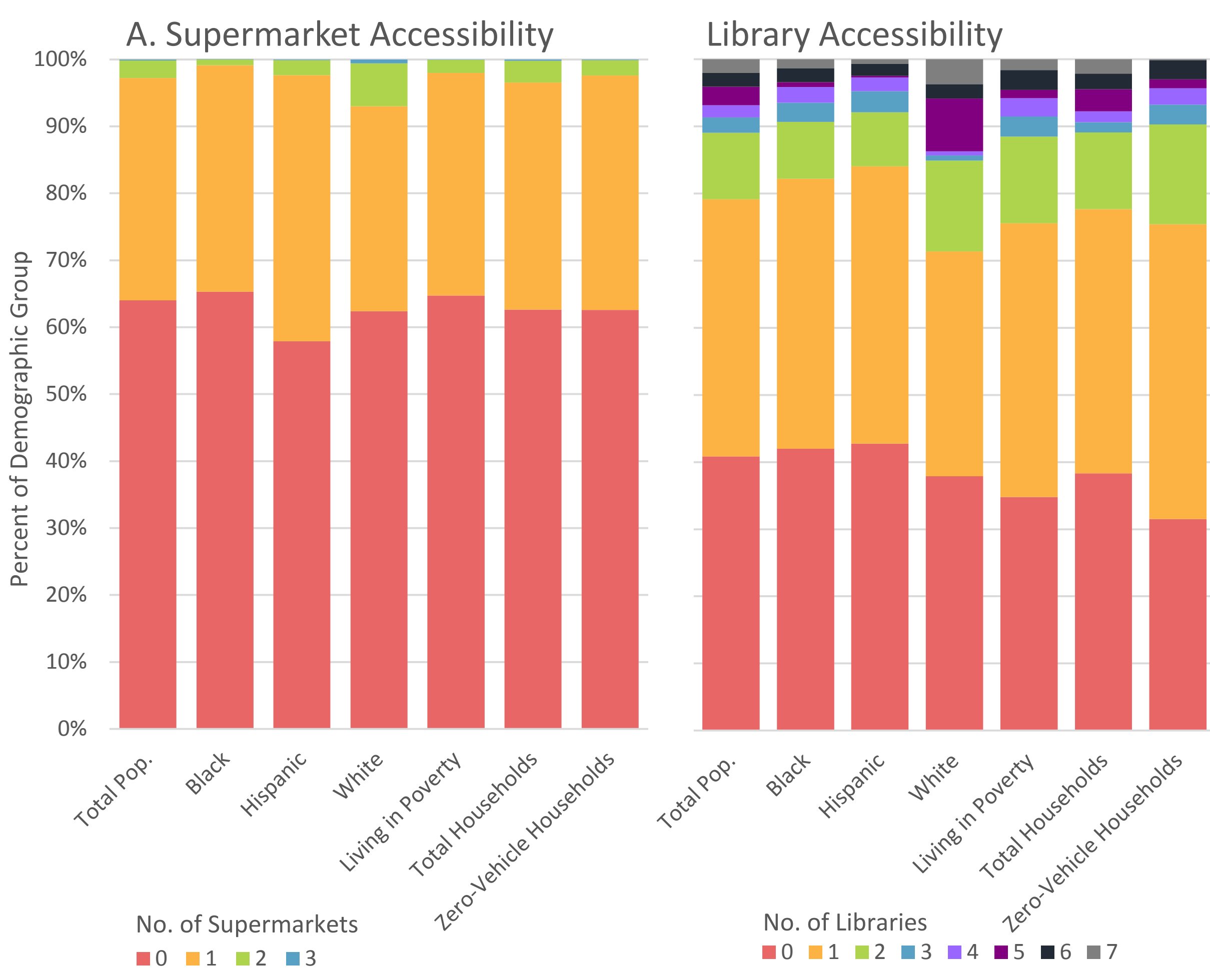


**Figure 18. Demographic Variation for Performance Measures 5 and 6**

Space- and place-based accessibility measures were both sensitive to the service area generation and to the characteristics of the LTS network, while place-based measures (PM 3, 4, 5, and 6) were also dependent on local land uses. High-stress roadways that limit the service areas are the main driver of low accessibility in some area; in other areas lack of businesses or lack of particular types of businesses is the main driver. For example, neighborhoods in West Baltimore including Harlem Park, Franklin Square, Union Square, Upton, and Poppleton had large service areas, high street distance, and high business totals, but lacked access to a supermarket. Instead, their business totals were driven by the multitude of pharmacies in the area. In contrast, some neighborhoods in Northeast Baltimore including Arcadia, Moravia-Walther, Beverly Hills, and Overlea had small service areas, but a supermarket was among their few accessible businesses. It is important to note that accessibility results reflect the sensitivity of the service area calculation to intersection LTS classification and to neighborhood centroid placement.

## Project Prioritization

The project prioritization results are meant to: 1) demonstrate the variability in rankings among performance measures and demographic criteria, and 2) offer a possible approach to balance accessibility and equity based on the parameters set in this study. The results are not meant to be a final recommendation for altering the prioritization in Baltimore's Bike Master Plan.

There are several different prioritization approaches. A justice-based prioritization would focus on infrastructure investment for communities that traditionally have been excluded from and negatively affected by transportation plans and projects, even if it means initially building a disconnected network. An accessibility-based prioritization would maximize accessibility performance measures. A "start centrally and connect out" approach is more similar to the Bike Master Plan's short-term priority list[5] shown in blue (Figure 19).

[5] Note that the project list in the plan is slightly different from the list used for this study, so prioritization results can only be compared approximately.

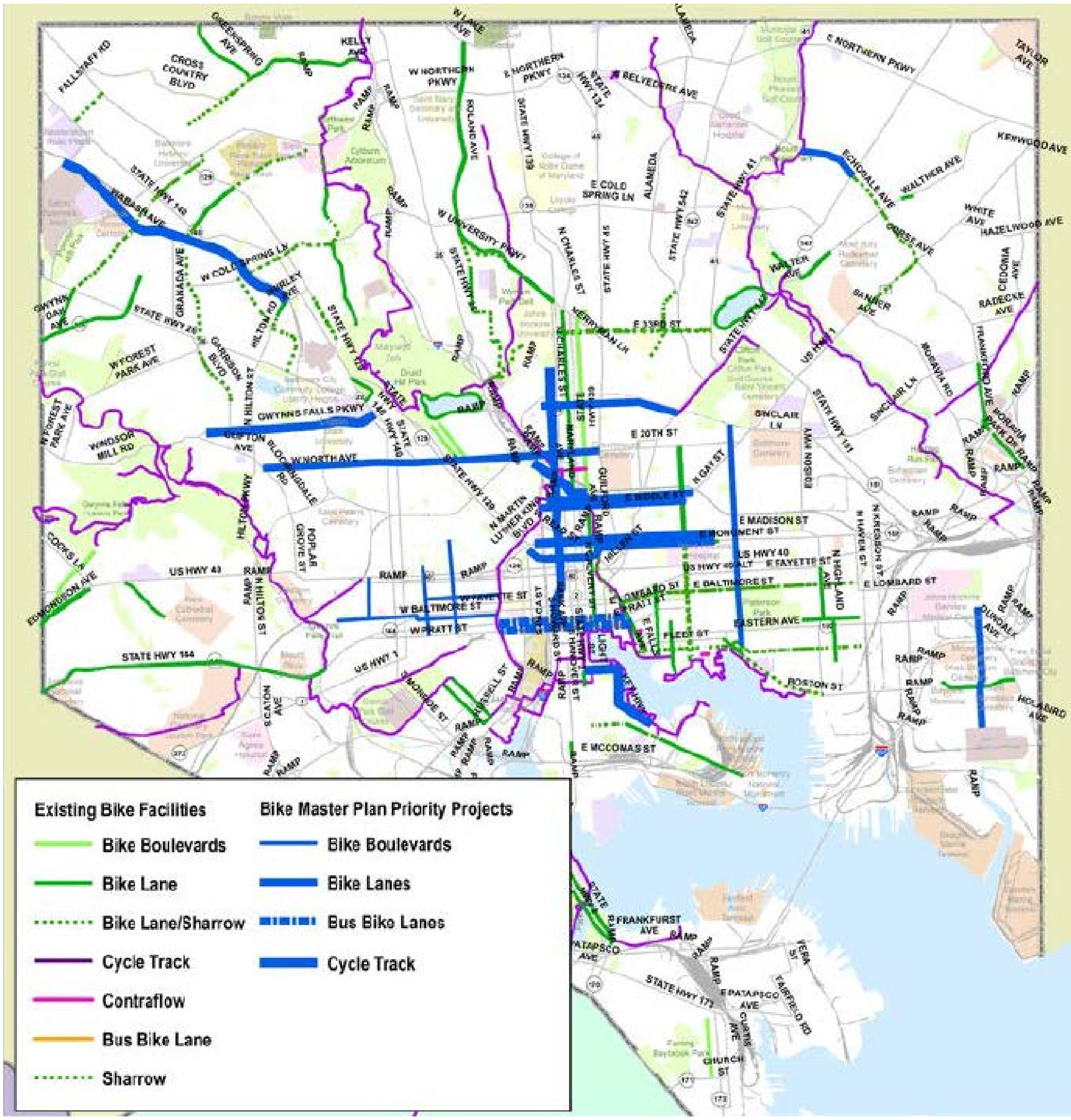


**Figure 19. Short-Term Priorities, Bike Master Plan 2015**

(Source: City of Baltimore, 2015, pg. 33)

Results for accessibility-based prioritization are followed by results for justice-based prioritizations; areas of overlap are identified and proposed to be top priorities for short-term implementation.

Before identifying top performers for accessibility, projects with no impact were first examined. Out of 106 projects, 15 projects had no impact on the accessibility performance measures, often because the underlying street links were already categorized as low-stress, as shown in Figure 20. A list of these projects can be found in Appendix B, Table 1a.

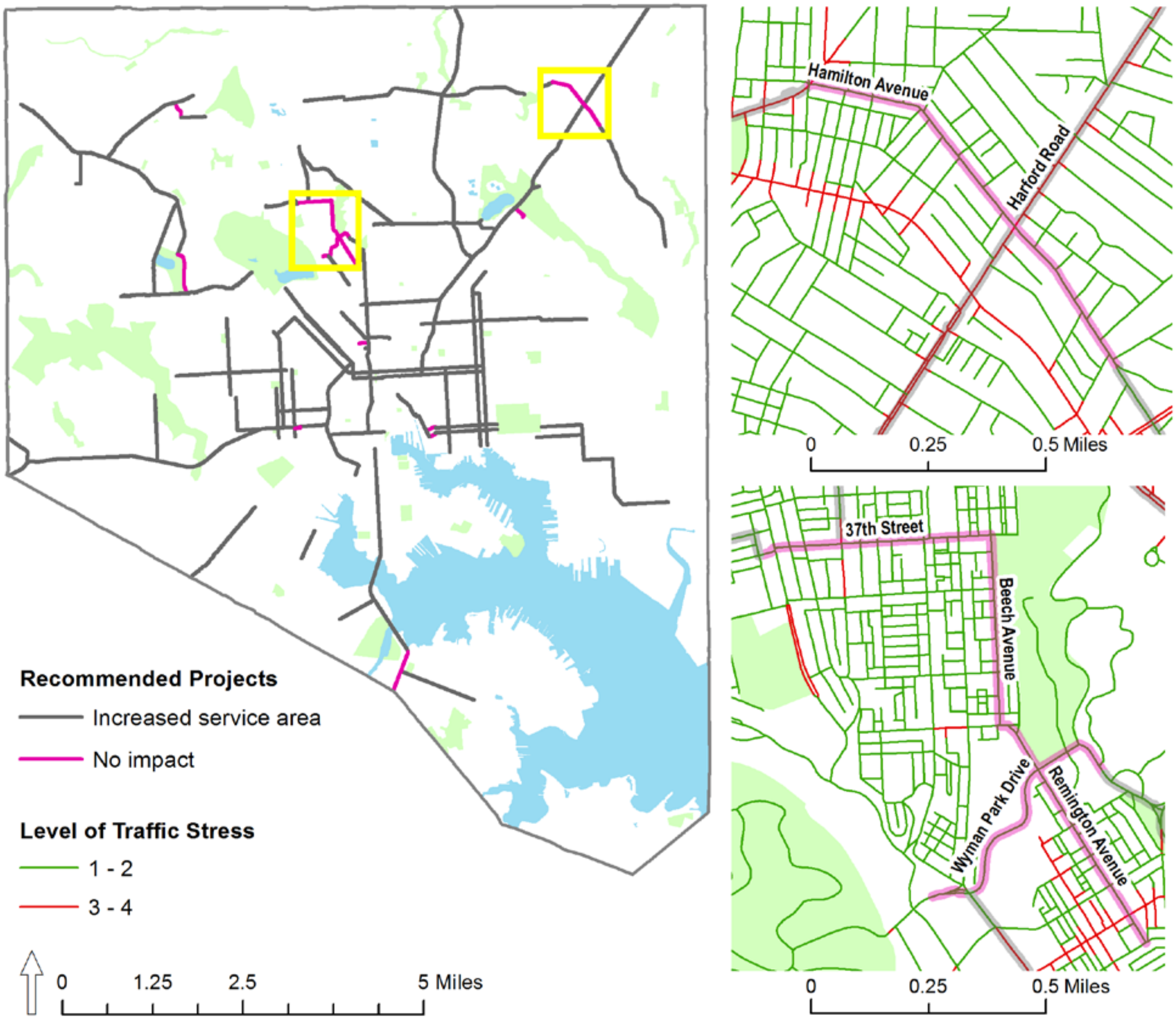


**Figure 20. Projects with No Impact**

All project rankings can be seen in Appendix B. Table 9 shows the top-performing projects according to each of the six performance measures. As demonstrated in the table, the top performers are in different areas of the city depending on the performance measure used in the ranking. However, two projects on West Biddle Street and Carrollton Avenue were each the number one performer for multiple performance measures.

**Table 9. Top Ranked Projects by Performance Measures**

| ID | Name | Project Length (mi) | Ranked by: | Accessibility Gain |
|---|---|---|---|---|
| 64 | The Alameda | 2.83 | PM 1 | 18.29-square-mile service area increase |
| 97 | Maryland Avenue Cycle Track | 2.56 | PM 2 | 280.33-mile street distance increase |
| 50 | West Biddle Street | 0.06 | PM 1N | 62.89-square-mile service increase per mile of project |
| | | | PM 2N | 2846.42-mile street distance increase per mile of project |
| 57 | Monument Protected Bike Lane | 1.84 | PM 3 | Cumulative increase of 321 businesses |
| 102 | West Baltimore Bike Boulevard Carrollton | 0.93 | PM 3N | Cumulative increase of 58 businesses per mile of project |
| | | | PM 4 | 23 neighborhoods have new access to all four business types |
| | | | PM 5 | 24 neighborhoods have new access to at least one supermarket |
| 66 | Harford Road | 1.70 | PM 6 | 8 neighborhoods have new access to at least one library |

Since some projects were top performers across multiple measures, the top-ranked projects for each performance measure were consolidated and then ranked again by the number of performance measures for which the project was highly ranked, as shown in Table 10. Normalized and non-normalized measures were not double-counted; therefore, projects like Mount Royal Avenue were ranked as performing well for five measures instead of eight, for example.

Projects that are part of the Downtown Bicycle Network, including Maryland Avenue Cycle Track (already completed) and planned protected bike lanes on Monument and Madison Streets would result in multiple accessibility gains. However, many projects which are not currently in the Bicycle Master Plan's short-term priority list were among the most impactful projects, including six segments along Harford Road. As expected, shorter projects tended to rank more highly using the normalized measure, but some projects, such as those along Belvedere Avenue, scored highly for both variations of multiple performance measures. The 44 projects in Table 10 were cross-listed with the top-ranked projects in Table 11, resulting in six projects that would maximize accessibility for disadvantaged populations.

**Table 10. Rankings across Multiple Measures**

| ID | Name[1] | Project Length (mi) | No. of PM for which project is highly ranked[2] | PMs for which project is highly ranked[3] |
|---|---|---|---|---|
| 66 | Harford Road | 1.70 | 6 | 1, 2, 3, 4, 5, 6 |
| 88 | Harford Road | 0.39 | 5 | 1N, 2N, 3N, 4, 5 |
| 20 | Mount Royal Avenue | 0.87 | 5 | 1, 1N, 2, 2N, 3, 3N, 4, 6 |
| 57 | Monument Protected Bike Lane | 1.84 | 5 | 1, 2, 2N, 3, 3N, 4, 6 |
| 97 | Maryland Avenue Cycle Track | 2.56 | 5 | 1, 2, 3, 3N, 4, 6 |
| **50** | **West Biddle Street*** | **0.06** | **4** | **1N, 2N, 3N, 6** |
| **17** | **Belvedere Avenue*** | **0.18** | **4** | **1, 1N, 2, 2N, 3N, 6** |
| 23 | Belvedere Avenue | 0.53 | 4 | 1, 1N, 2, 2N, 3N, 6 |
| 86 | Harford Road | 0.65 | 4 | 1N, 4, 5, 6 |
| 56 | Madison Protected Bike Lane | 1.80 | 4 | 1, 2, 3, 3N, 6 |
| 64 | The Alameda | 2.83 | 4 | 1, 2, 3, 6 |
| 5 | Wyndhurst Avenue | 0.55 | 3 | 1N, 2N, 6 |
| 22 | Roland Ave | 0.80 | 3 | 4, 5, 6 |
| 102 | West Baltimore Bike Boulevard Carrollton | 0.93 | 3 | 3, 4, 5 |
| 72 | Martin Luther King Junior Boulevard | 1.34 | 3 | 1, 2, 3, 3N |
| 89 | Washington Street | 1.89 | 3 | 1, 2, 3 |
| **7** | **Sinclair Lane*** | **0.09** | **2** | **1N, 2N** |
| 94 | 33rd Street Median Bike Path | 0.41 | 2 | 4, 5 |
| 87 | Harford Road | 0.44 | 2 | 4, 6 |
| **99** | **West Baltimore Bike Boulevard Smallwood*** | **0.46** | **2** | **1N, 2N** |
| 63 | University Parkway | 0.66 | 2 | 4, 5 |
| 43 | Homeland Avenue | 0.67 | 2 | 1N, 6 |
| 68 | Harford Road | 0.93 | 2 | 2N, 5 |
| 28 | University Parkway | 1.21 | 2 | 4, 5 |
| 62 | Eutaw Place | 1.86 | 2 | 4, 5 |
| **96** | **Gwynns Falls Median Bike Path*** | **0.55** | **1** | **5** |
| 84 | Harford Road (north) | 0.72 | 1 | 4 |
| 73 | Pratt Street | 0.75 | 1 | 3, 3N |
| 81 | The Alameda (South) | 0.97 | 1 | 5 |
| **37** | **Bentalou Street*** | **1.06** | **1** | **6** |
| 1 | E Patapsco Avenue | 1.09 | 1 | 6 |
| 53 | Wabash Avenue | 2.88 | 1 | 5 |

[1] Asterisk (*) and bold text denote that project is also a priority based on the demographic ranking
[2] This ranking is based on the top 10 projects for PM 1, 1N, 2, 2N, 3, and 3N and on all projects that scored a "Yes" on PM 4, 5, 6—13, 13, and 16 projects, respectively.
[3] These are the performance measures that are counted in the fourth column.

The ranking in Table 11 represents a consolidation of the top 10 projects impacting black, low-income, and/or carless residents presented in Appendix B, Tables B7, B10, and B11. These projects are then sorted by their impact across multiple disadvantaged groups, while drawing primarily on community concern about lack of bike infrastructure serving majority-black neighborhoods. Since Baltimore's Hispanic communities are much smaller and concentrated in one area, they are not included in this table; see Appendix B, Table B8 for projects that may best serve Hispanic residents.

**Table 11. Rankings across Multiple Indicators of Disadvantage**

| ID | Name[1] | Project Length (mi) | At least 90% of affected residents are black | At least 35% of affected residents are in poverty | At least 50% of affected households have no vehicle |
|---|---|---|---|---|---|
| 77 | Hanover Street | 0.15 | X | X | X |
| 33 | Cherry Hill Road | 0.54 | X | X | X |
| 75 | Hanover Street | 0.89 | X | X | |
| **50** | **West Biddle Street*** | **0.06** | | **X** | **X** |
| 80 | Eutaw Place | 0.25 | | X | X |
| 100 | West Baltimore Bike Boulevard Lexington | 0.72 | | X | X |
| 98 | West Baltimore Bike Boulevard Hollins | 1.23 | | X | X |
| 2 | Frederick Avenue | 1.57 | | X | X |
| **17** | **Belvedere Avenue*** | **0.18** | **X** | | |
| **96** | **Gwynns Falls Median Bike Path*** | **0.55** | **X** | | |
| **37** | **Bentalou Street*** | **1.06** | **X** | | |
| 54 | Wabash Avenue | 0.75 | X | | |
| 45 | Frederick Avenue | 0.89 | X | | |
| 26 | Hilton Street | 0.92 | X | | |
| 71 | Hilton Street | 1.40 | X | | |
| **99** | **West Baltimore Bike Boulevard Smallwood*** | **0.46** | | **X** | |
| 35 | Washington Street | 0.20 | | X | |
| **7** | **Sinclair Lane*** | **0.09** | | | **X** |
| 31 | Eutaw Place | 0.44 | | | X |
| 38 | McCulloh Street | 1.14 | | | X |

[1] Asterisk (*) and bold text denote that project is also a priority based on the accessibility rankings

Projects listed in the previous two tables are shown in Figure 21. Darker lines or buffers represent higher impact across more measures.

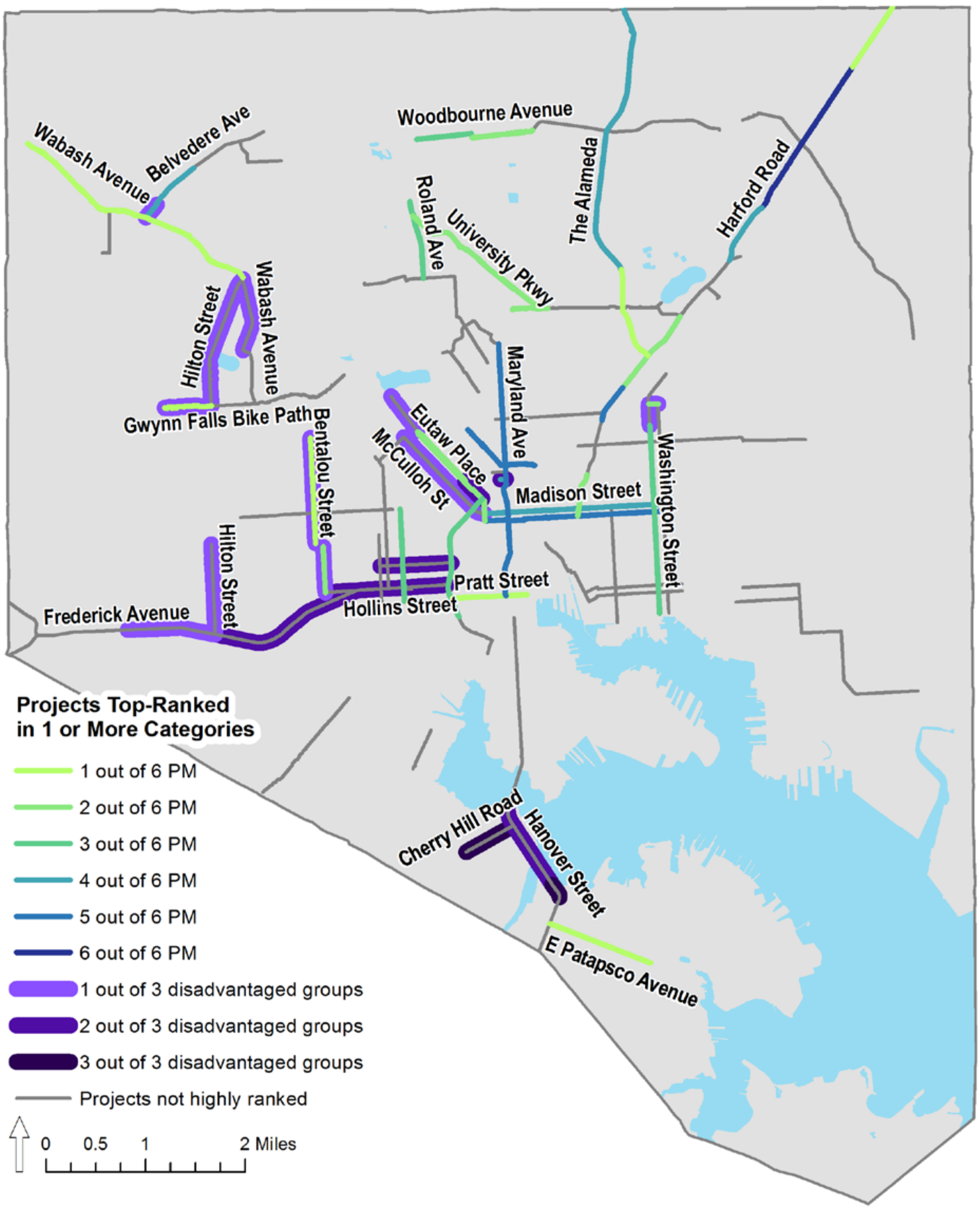


**Figure 21. Projects Highly Ranked by Performance Measures and/or Demographics**

The accessibility-based approach yields results that overlap with the plan's existing prioritization, but also highlights LTS 4 corridors like Harford Road and The Alameda, which serve both commercial areas and racially diverse neighborhoods with high numbers of low- and moderate-income residents. The justice-based approach yields results that only coincide with accessibility results for projects in West Baltimore, but not further west along Frederick Avenue and in the Cherry Hill area, where projects would serve the most disadvantaged residents. To balance these two approaches, the “equity of accessibility” approach would prioritize for shorter-term implementation the six projects shown as a combination of green/blue lines and purple buffers, since they could meet both distributive justice goals while potentially improving low accessibility. Note that the six high-priority projects are based on the upper range for concentration of disadvantaged populations; many projects that highly ranked for accessibility would also likely reduce disparities. Projects that would increase accessibility to supermarkets and libraries for underserved populations should be prioritized; for example, projects along Wabash Avenue in the northwest and Harford Road in the northeast.

# DISCUSSION

In general, the project rankings yielded intuitive results relative to the baseline. However, in some cases the baseline results may not have been realistic because PM 2 through 6 were dependent on the initial service area size (PM 1), yet these services areas may not be accurate for several reasons.

## Service Areas

Assuming every crossing link is correctly classified, it appears that the combination of LTS with Network Analyst routing algorithms can overestimate service areas in some cases and underestimate them in others. Any neighborhood near the edge of the network would have a smaller chance of having a large service area, since all routes end at the city boundary. Even though a computer can ‘find’ every low-stress route possible until reaching the distance cut-off, human beings travel using limited mental maps, as noted by Wang, et al. (2016), and would be more likely to choose direct routes. A person traveling by bicycle would be inclined to draw hard barriers at LTS 4 roadways or at high-volume roads if finding a low-stress crossing point involves going out of one’s way to a signalized intersection, and knowing where that intersection is in the first place. Therefore, the realistic range of service area sizes is likely narrower than found in this case study. However, even that range would be based on the distance threshold of two miles; it is more likely that some individuals would be comfortable bicycling much longer, and others would find two miles to be too far. Incorporating individual accessibility into this method in a manner similar to Páez et al. (2010) would be a challenge without detailed and current travel survey data.

The second reason that service areas could be inaccurate is their sensitivity to the restriction settings. Functionally, this analysis collapsed four LTS categories into two, not only based on the literature but also because of service area test results showing that allowing LTS 3 did not significantly expand the service area. However, future analysis should test allowing only LTS 1 to represent the service area available to cautious bicyclists. A shortcoming of analyzing service areas solely based on the LTS road network is that it ignores the fact that bicyclists can become pedestrians (or ride on the sidewalk, whether or not it is legal). Future research could examine ways to incorporate sidewalks into a multimodal non-motorized network in which low-stress roads are preferred, but the sidewalk network is activated when the LTS is too high. This addition would likely expand service areas. Incorporating traffic volume as an additional restriction could have made service areas more realistic, but like LTS 4 streets with signalized intersections, high-volume streets would not necessarily block a crossing route. Also, a more detailed street network that includes street direction and elevation would change the accessible routes. Despite the impossibility of perfectly representing accessibility experienced by different people in different locations, service areas could be used to gather input from the public about which routes and crossing points are most often used, and whether the accessible destinations are truly accessible on the ground.

Neighborhood-level results for PM 1 and 2 varied slightly, but when aggregated to the project level, the high and low performers tended to be the same set of projects in a slightly different order, even when normalized. This makes sense, because differences in street layout across neighborhoods tended to even out when aggregated to the project level. The redundant results suggest that PM 2 could be eliminated. However, this measure would be useful for a more robust cross-mode comparison with motor vehicle accessibility.

## Business Performance Measures

The supermarket and library access measures were perhaps the most meaningful measures, because they allowed for the identification of clear accessibility disparities. The fact that supermarkets tended to be the limiting factor in the business diversity measure is consistent with McNeil's findings that lack of bicycle accessibility to grocery stores detracted the most from neighborhood bikeability scores (2011). White residents have disproportionately higher access to more than one supermarket, despite smaller service areas. These results were unsurprising, given that Grengs found the similarly segregated city of Detroit to have disparities in supermarket accessibility by auto (2015). Although auto accessibility to supermarkets was found to be five times higher on average compared to bicycle accessibility, it was also more variable, and improving bicycle accessibility would not necessarily overcome the phenomenon of food deserts in communities of color. Especially for supermarkets, a strength of the performance measure is the ability to isolate more universally necessary destinations from a 'basket' that includes destinations catering to more specific clientele. However, PM 5 and 6 are also most sensitive to data accuracy. Though the business point data were cleaned, they would be missing new locations and could include any locations that have since closed. If a similar measure were to be formalized in a planning process, it would be critical to cross-check and supplement business point data from multiple sources. The business diversity measure tended to be driven by supermarket and library accessibility, but it is useful for identifying projects that 'complete' the missing piece of McNeil's bikeable neighborhood concept (2011), especially if more destination types are included.

The business total measure is the least useful for two reasons. First, the neighborhood-level (baseline) measure could include many of the same type of business. While this would capture the availability of options, having access to twenty brick-and-mortar banks or twenty pharmacies would not truly represent a high level of accessibility for an individual who does not have multiple accounts with different banks or only needs access to a few convenient pharmacies. A modified 'basket' version of the business total, similar to what McNeil (2011) and Lowry et al. (2016) propose, would be more useful than an absolute total. Whereas Lowry et al. required that at least of two of each type needed to be accessible to count in their accessibility metric (2016), McNeil awarded varying amounts of admittedly arbitrary points to each destination type up to a certain number of occurrences to create a composite score (2011). McNeil's approach of setting different occurrence thresholds based on destination type would work well to modify the business total measure such that after, for example, three pharmacies were counted in a service area, other accessible pharmacies no longer counted toward the business total.

Second, the project-level business total was cumulative across all affected neighborhoods, without accounting for overlap in business locations. While this measure is useful for comparing projects, it can be difficult to interpret. At the project level, it serves more as an accessibility impact measure weighted by the number of neighborhoods. Long projects serving downtown naturally rose to the top of the PM 3 rankings. The normalized version of PM 3 is perhaps more useful for identifying projects that would expand business accessibility for short projects that create new connections to downtown or longer projects in outlying areas that open up access to commercial strips along otherwise high-stress arterials. A possible modification to the project-level business total would be to aggregate only the unique locations into a total and to keep the number of affected neighborhoods, or weight, as a separate component of the business total measure. Future research should also translate project-level accessibility gains back to the neighborhood level as projects are built to track progress against the baseline measures over time.

## Project Prioritization

Lack of businesses and neighborhood land use are the main drivers of low accessibility measures in some areas, whereas high-stress roadways are the main driver of low accessibility measures in other areas. One drawback of the performance measures is that they do not quantify the degree to which each of these aspects contributes to low accessibility measures, so as to identify the best lever for improvement to prioritize in different neighborhoods. Some neighborhoods will have low business accessibility no matter what, if they are dominated by residential land use. A larger absolute improvement in business accessibility for residents who choose to live in suburban-style areas should not necessarily be prioritized over a smaller marginal improvement in accessibility for in disinvested urban neighborhoods that could support more commercial development. Effective increases in accessibility would not necessarily be accomplished with bicycle infrastructure; instead, projects would need to be integrated with economic and community development efforts.

A few issues arise in prioritizing projects with a method that relies heavily on LTS. While LTS is useful for identifying street comfort and network connectivity challenges, it does not translate directly into the level of investment necessary to achieve LTS 1 or 2. It can be misinterpreted by the public as mischaracterizing their neighborhoods ("The streets in my neighborhoods are all LTS 1 on the map, but I don't see a single bike lane outside") or by decision makers as justifying less investment ("The streets are already low-stress, so why build a bike facility?"). Furthermore, large service areas due to inherently low-stress streets rather than stress-reducing bicycle infrastructure can obscure disparities in investment patterns. The community-identified injustice regarding bicycling in Baltimore is largely about the distribution of infrastructure, not the distribution of LTS 1 streets. Service area size and distance alone should not be used to justify lack of investment.

To address the issue of infrastructure investment, the LTS network could be supplemented with information about what type of facility is present on each link. It would then be possible to separate out the proportion of the service area network that is inherently low-stress as opposed to invested low-stress. A measure similar to Lowry et al.'s centrality metric (2016) might also be used to determine whether the most central links in the service area were ones that had facilities. Prioritizing fair distribution of bicycle facilities could result in a disconnected network. However, having facility information for each link would also allow for projects that connect to existing facilities to receive higher priority. Though this approach could overemphasize connections to the downtown bicycle network, Baltimore’s network of trails is dispersed throughout the city and could balance out the pull to the center.

## Equity

Given that many of Baltimore’s neighborhoods are still very segregated, ranking by proportions yielded the expected result that projects impacting the highest proportions of disadvantaged populations ended up in the so-called “Black Butterfly” areas. This approach prioritizes concentration over population; an alternative would be to rank by the population counts for each disadvantaged group. The reason for not doing so in this case study was because if a service area was overestimated, then a project quite far away could still expand the reach of that service area, and that entire neighborhood’s population would be counted. The use of proportions made it possible to capture the demographic characteristics of the affected area without inflating the number of people affected. With more accurate service areas, ranking by population counts could be better, especially for more racially and economically integrated neighborhoods.

Baseline neighborhood results showed that residents living in poverty and zero-vehicle households tended to score similar to or better than the total population for all performance measures. However, these results should not be used to de-prioritize projects that would serve these populations, because true accessibility may actually be much lower. For example, business locations contributing to high accessibility scores may not be affordable, residents would work shifts that make it hard to go to theoretically accessible businesses, or residents may not be able to afford a bicycle. One way to better prioritize projects for zero-vehicle households would be to create a performance measure for the ratio of bicycle- to auto-accessible streets, and prioritize projects that decrease this ratio for areas with high numbers of zero-vehicle households.

The project-level performance measures are based on the premise that accessibility benefits accrue not only to the neighborhoods where the project is located, but also to adjacent and even nonadjacent neighborhoods if they create more low-stress routes and open up more destination options. However, accessibility benefits can be defined in various ways by different users. In a city where the conversation is still focused on getting access to the infrastructure itself, hypothetical accessibility to a faraway business may not be valued. For example, the Maryland Avenue Cycle Track was already completed in 2016, thus allowing for a retrospective look at how it would have fared in the rankings. It rose to the top of the non-normalized rankings for service area size, distance, and total business accessibility measures due to its central location and project length. It was not top-ranked for indicators of disadvantage, but if the number of neighborhoods affected had been another performance measure, Maryland Avenue Cycle Track would have been ranked number one at 60 neighborhoods with a racially and economically diverse population of over 150,000 affected people. Nonetheless, its hypothetically wide-ranging impact may be less important to disadvantaged communities than a smaller project with neighborhood-scale impacts. Dr. Brown observed:

> “Last night, I saw a pedestrian walking in the Maryland Ave. protected bike lane…I predict there'll be bikes, scooters, skateboards, hoverboards, skates, and walkers in the protected White L bike lanes when it really gets warm…Now here's the kicker: this wonderful infrastructure is found in

> the White L but not in the Black [Butterfly]… Granted, bike infrastructure (like protected bike lanes) will have a different flavor in the Black [Bufferfly]. I suspect it would have more people walking in it and children frolicking in it. People might even pull out lawn chairs and sit next to it or barbeque near it. But it would be a community space there too! So it's a pity and a shame that one part of our city will have this and the other will not.” (Brown, 2017, March 10)

Brown’s point about residents wanting to enjoy bike infrastructure as a community space and not just a transportation route means that a project that is a mile away, even if it dramatically increases hypothetical accessibility, may not create benefits for a community that wants enjoy the physical infrastructure itself. Therefore, balancing the accessibility measures with the demographic rankings becomes even more important for ensuring that projects that ostensibly have broad impacts are not prioritized at the expense of projects that would, at a smaller and thus more definite scale, benefit low-income residents and communities of color. This is not to say that Maryland Avenue Cycle Track should not have been built, but rather that for every project that is top-ranked for accessibility measures but not demographic criteria, a parallel justice-based approach would could prioritize another project that specifically benefits disadvantaged neighborhoods. Implementation of these projects would need to proceed based on the neighborhood’s vision for how they would want the infrastructure to serve them, and with attention to concerns about gentrification.

## CONCLUSION

This study presents a bicycle project prioritization method that balances both accessibility and equity goals. Using six accessibility performance measures and four demographic indicators of disadvantage, the method is demonstrated for 278 neighborhoods and 106 proposed bicycle projects in the City of Baltimore. The project rankings had some overlap with the short-term priorities in Baltimore’s 2015 Bike Master Plan, notably for centrally-located cycle tracks and protected bike lanes. However, the results from this case study also highlight projects in other areas, specifically those that would increase overall business, supermarket, and library accessibility along current high-stress arterials, and those that would serve the neighborhoods most disadvantaged in terms of racial segregation, high poverty rates, and high rates of not owning a vehicle. This method also demonstrates how a quality of service measure such as LTS could be used to evaluate accessibility using network-based analysis. Suggestions for how cities can ensure that their LTS networks have maximum utility and reliability for similar types of analyses are offered.

Low-stress bicycle accessibility to businesses is a function of both the quality and comfort of the bicycle network and the neighborhood-level land use and economic conditions. Though the results are meant to be used by bicycle planners to identify and prioritize bicycle network improvements that increase access to nearby businesses, they could also be used to advocate for supermarkets in food deserts or other commercial development. System-wide bicycle accessibility analysis is a starting point for greater integration of transportation planning, land use planning, and community and economic development. However, equitable distribution of bicycle investments would recognize that especially initially, access to the infrastructure itself can be as important as the broader accessibility benefits, particularly in cities with great inequality and great ambition to be bikeable.

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# APPENDIX A. TECHNICAL DOCUMENTATION

## LTS Network

To prepare the network to be built in Network Analyst, links of the following functional classes (as defined by Maryland State Highway Administration) were deleted: Interstates and Principal Arterials including I-395, I-83, I-95, and I-895 and grade-separated Freeways and Expressways including I-170. South President Street, though classified as a Freeway, was retained as it is at grade and has a bike lane. Next, all links classified as ramps were deleted except those that connected onto parkways with a sidewalk (such as Hilton Parkway) or that created a connection for someone wanting to exit off a roadway that transitions into a grade-separated highway further down (such as Howard Street and Mount Royal Terrace).

The original LTS classification was in a single column, but to create restrictions in Network Analyst, it had to be split into four separate columns.

These fields were added as restrictions when building the network by setting the evaluator to equal 1 for each LTS value, as shown in Figure A22.

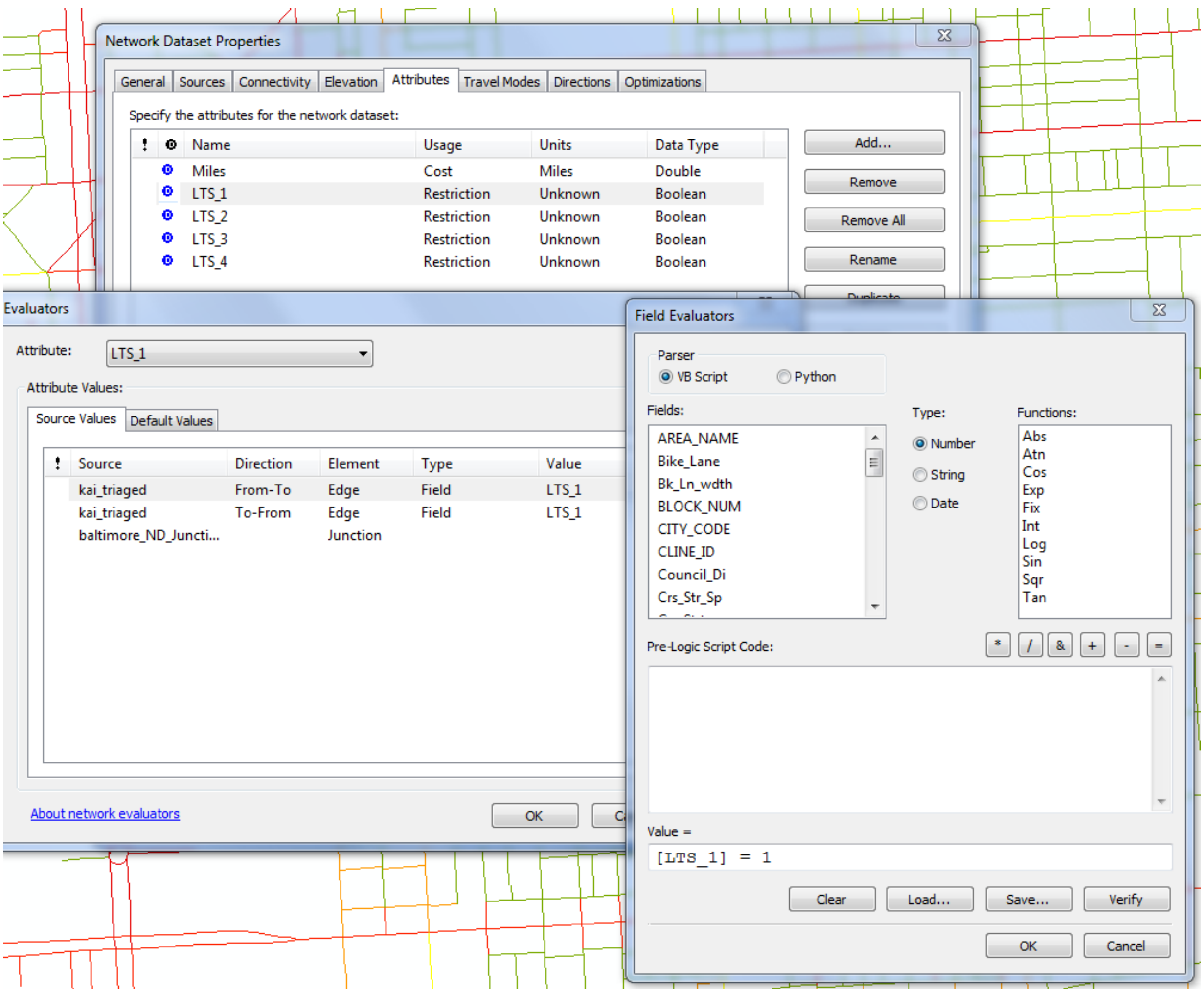


**Figure A22. Setting LTS Restrictions**

## Adding in Trails

Trail segments that duplicated portions of the street network were removed, and trail crossings with the street network were manually inspected to ensure that trail links were snapped to the street junctions. Trail vertices were removed in places like bridges where routes needed to stay on the trail instead of jumping onto the roadway; street vertices in the LTS file were similarly treated in select locations with bridges. The calculate field geometry tool was used to add the trail length, and all trail segments were designated LTS 1 using the field calculator. The LTS file and the trail file were the two inputs into the Build Network function, using "Any Vertex" connectivity. Finally, trail crossings were tested by running ESRI ArcMap Network Analyst routes between selected points to ensure that routes could use both trails and streets. Routes that did not use the trail were found have incorrectly snapped vertices; once vertices were manually napped at all crossings, every test functioned as expected.

## Preparing the Projects Layer

Since the projects layer did not align with the street network in all places, a series of steps were used to prepare it for analysis. The Densify tool was used to add more vertices to the project segments. The Snap tool was then applied successively at higher and higher tolerances (from 10 feet to 50 feet) until the Select by Location tool could be used to select underlying streets that shared a line segment with the project layer. Figure A23 shows that pre-processing, few underlying streets were able to be selected from based on project location (projects are in royal blue, black bubbles indicate street selections in cyan blue), whereas post-processing, almost all links were selected (black bubble indicates the inverse—the only project not matched to underlying street links).

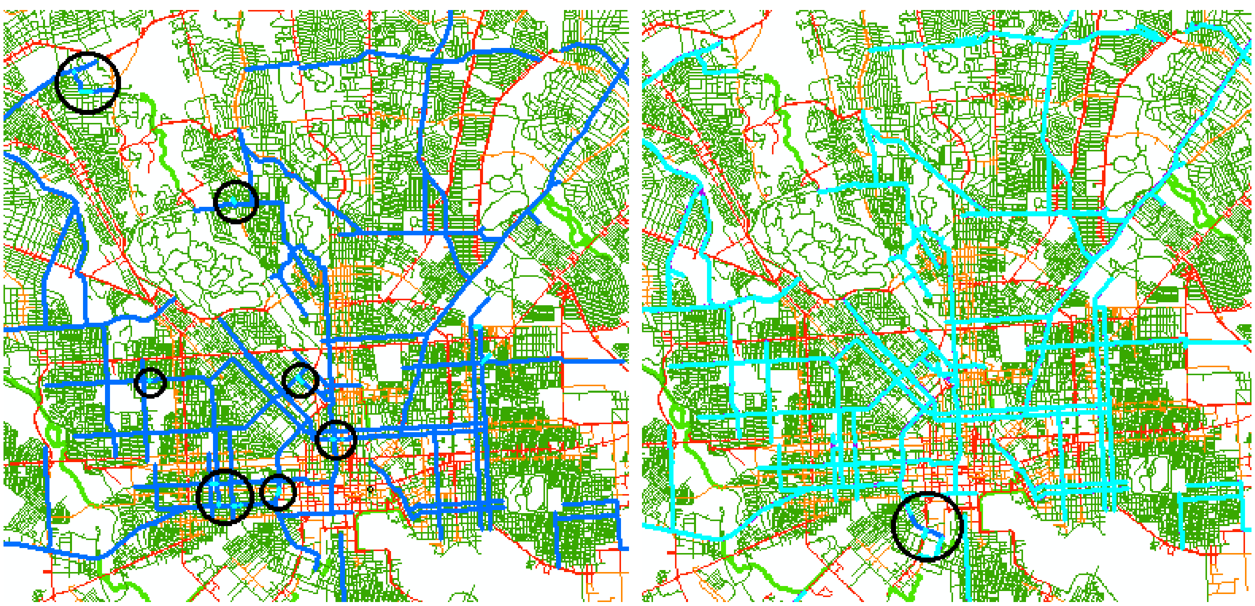

**Figure A23. Selection of Underlying Street Links by Shared Location with Project Recommendations – Pre- and Post-Processing**

A project layer consisting of links matching the street network would have allowed for more reliable results, especially for projects along streets composed of parallel links representing medians, which resulted in incomplete snapping. Figure A24 shows Project 94 along 33rd Street, which has a median. From west to east, the project snapped to the northern side of the road and then to the southern side. The new service area (cyan blue transparency without a grey border) was still blocked by the LTS 4 links on the northern side.

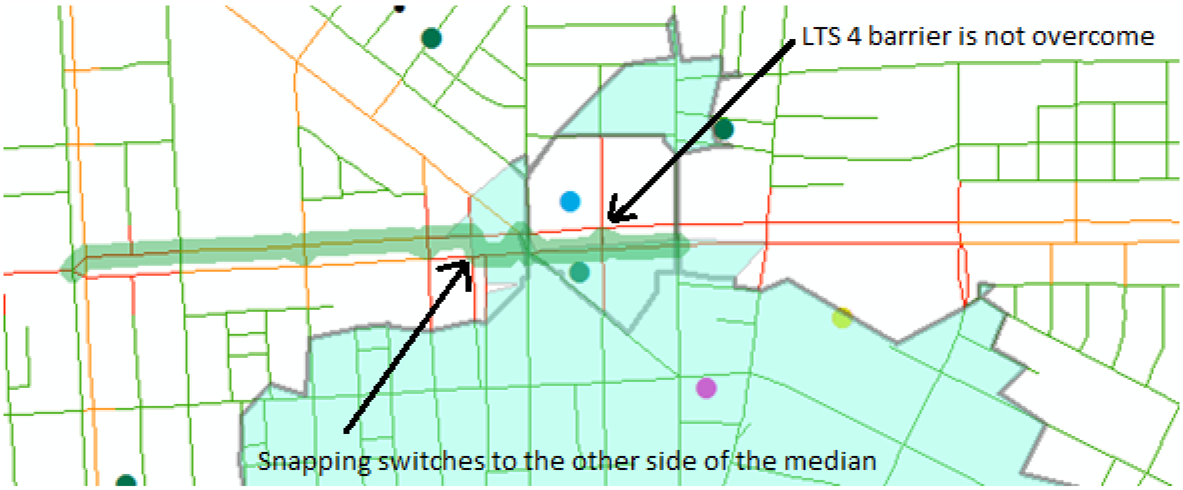


**Figure A24. Snapping Inconsistencies on Streets with Medians**

Manually adjusting every project was out of the scope of this study.

## Neighborhood Centroids

A preliminary generation of service areas showed that a number of neighborhoods had their centroid blocked from accessing a route and therefore had no service area, even if the next closest streets were low stress. For each neighborhood that contained low stress streets but whose centroid was snapping to the nearest high-stress street, the centroid was manually moved by the distance shown in Table A12 to allow access to the nearest low-stress street. Fourteen neighborhoods would have not have had any accessible routes no matter the centroid placement, so these are not included below.

**Table A12. Centroid Adjustment**

| Neighborhoods, in descending order of adjustment distance | Distance that centroid was moved (feet) |
|---|---|
| Penrose/Fayette Street Outreach | 565.3 |
| Carroll-South Hilton | 298.3 |
| Glenham-Belhar | 223.2 |
| Johnston Square | 197.9 |
| Stadium Area | 171.6 |
| Cheswolde | 152.3 |
| Guilford | 132.0 |
| Jonestown | 121.3 |
| Kernewood | 116.9 |
| Middle East | 109.0 |
| Glen | 105.5 |
| University Of Maryland | 104.5 |
| Graceland Park | 102.9 |
| Mid-Town Belvedere | 101.6 |

| | |
|---|---|
| Ednor Gardens-Lakeside | 87.5 |
| Downtown West | 86.8 |
| Charles Village | 83.6 |
| Remington | 80.4 |
| Broadway East | 76.7 |
| Medford | 71.5 |
| Penn-Fallsway | 65.1 |
| Park Circle | 63.1 |
| Fells Point | 48.5 |

## Service Areas

Along with the LTS restriction and distance cut-off, service area settings included: detailed polygons, trimmed 100 meters, multiple facilities merged by break value, and overlapping rings, as shown in Figure A25.

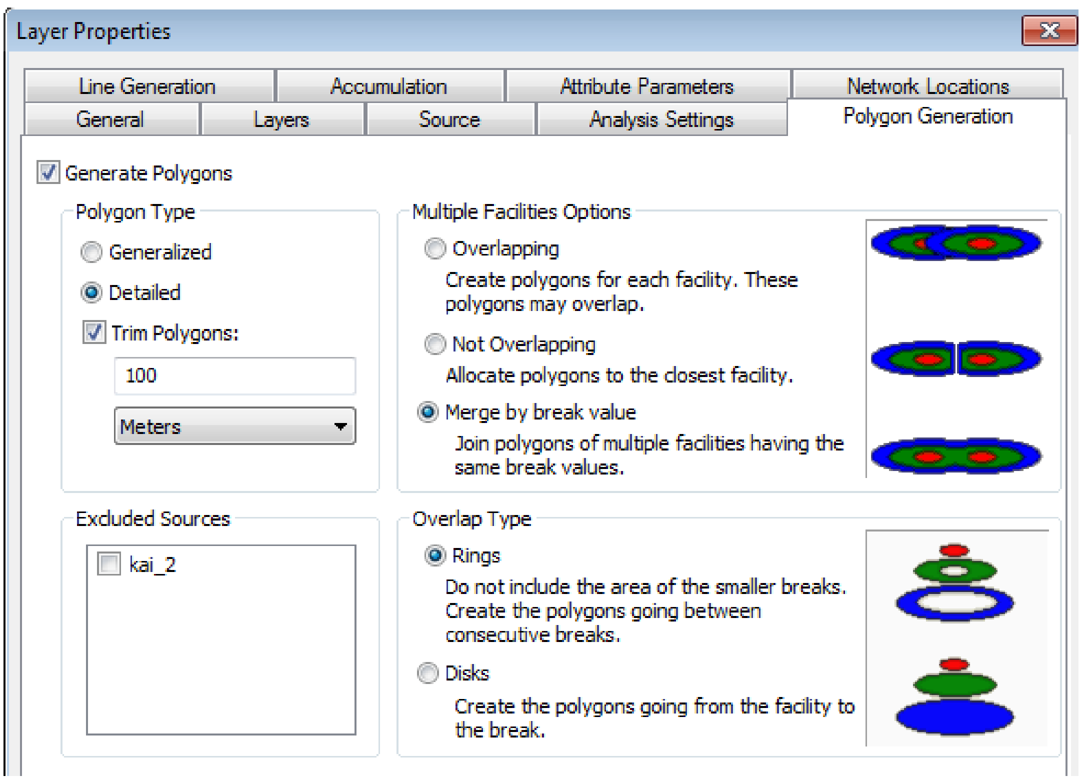


**Figure A25. Service Area Settings**

# APPENDIX B. PROJECT RANKINGS

## B1.1. PM 1: Ranked by cumulative service area gains across all affected neighborhoods

This table contains all 106 projects. Subsequent tables will only contain the top-ranked projects.

| ID | Name | Type | Project Length (mi) | Cumulative Service Area Increase (sq. mi) |
|---|---|---|---|---|
| 64 | The Alameda | Physically separated facility | 2.83 | 18.29 |
| 97 | Maryland Avenue Cycle Track | Physically separated facility | 2.56 | 17.4 |
| 57 | Monument Protected Bike Lane | Physically separated facility | 1.84 | 16.2 |
| 66 | Harford Road | Physically separated facility | 1.70 | 13.28 |
| 56 | Madison Protected Bike Lane | Physically separated facility | 1.80 | 12.23 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.87 | 8.37 |
| 23 | Belvedere Avenue | Physically separated facility | 0.53 | 8.23 |
| 72 | Martin Luther King Junior Boulevard | Physically separated facility | 1.34 | 8.17 |
| 17 | Belvedere Avenue | Physically separated facility | 0.18 | 7.8 |
| 89 | Washington Street | Wide Bike Lane buffer (P) | 1.89 | 7.59 |
| 25 | Frederick Avenue | Physically separated facility | 1.29 | 7.38 |
| 5 | Wyndhurst Avenue | Wide Bike Lane buffer (O) | 0.55 | 7.35 |
| 68 | Harford Road | Physically separated facility | 0.93 | 6.97 |
| 43 | Homeland Avenue | Wide Bike Lane buffer (O) | 0.67 | 6.58 |
| 86 | Harford Road | Physically separated facility | 0.65 | 6.5 |
| 2 | Frederick Avenue | Wide Bike Lane buffer (O) / Physically Separated | 1.57 | 5.71 |
| 99 | West Baltimore Bike Boulevard Smallwood | Bike Boulevard | 0.46 | 5.29 |
| 73 | Pratt Street | Physically separated facility | 0.75 | 5.01 |
| 71 | Hilton Street | Physically separated facility | 1.40 | 4.64 |
| 65 | Creston Avenue | Physically separated facility | 2.00 | 4.6 |
| 85 | Harford Road | Physically separated facility | 0.76 | 4.45 |
| 63 | University Parkway | Physically separated facility | 0.66 | 4.18 |
| 26 | Hilton Street | Physically separated facility | 0.92 | 4.08 |
| 88 | Harford Road | Physically separated facility | 0.39 | 3.79 |
| 92 | 33rd Street Median Bike Path | Physically separated facility | 0.88 | 3.72 |
| 50 | West Biddle Street | Wide Bike Lane buffer (O) | 0.06 | 3.59 |
| 22 | Roland Ave | Physically separated facility | 0.80 | 3.45 |
| 81 | The Alameda (South) | Physically separated facility | 0.97 | 3.44 |
| 28 | University Parkway | Physically separated facility | 1.21 | 3.37 |
| 62 | Eutaw Place | Physically separated facility / Wide Buffer Lane | 1.86 | 3.18 |
| 96 | Gwynns Falls Median Bike Path | Physically separated facility | 0.55 | 3.1 |
| 54 | Wabash Avenue | Wide bike lane buffer (O) | 0.75 | 2.96 |

| | | | | |
|---|---|---|---|---|
| 32 | Washington Boulevard | Wide Bike Lane w/ buffer | 1.36 | 2.7 |
| 7 | Sinclair Lane | Bike lane w/ buffer | 0.09 | 2.6 |
| 53 | Wabash Avenue | Physically separated facility | 2.88 | 2.56 |
| 45 | Frederick Avenue | Physically separated facility | 0.89 | 2.4 |
| 87 | Harford Road | Physically separated facility | 0.44 | 2.16 |
| 94 | 33rd Street Median Bike Path | Physically separated facility | 0.41 | 1.79 |
| 69 | Harford Road | Physically separated facility | 0.57 | 1.46 |
| 70 | Chester Street | Wide bike lane buffer (O) | 2.11 | 1.43 |
| 30 | Sisson Street | Wide Bike Lane buffer (O) | 0.50 | 1.19 |
| 84 | Harford Road (north) | Physically separated facility | 0.72 | 1.1 |
| 55 | Hanover Street | Physically separated facility | 1.96 | 0.96 |
| 19 | Calhoun Street | Wide Bike Lane (O) | 1.38 | 0.91 |
| 80 | Eutaw Place | Wide Bike Lane buffer (P) | 0.25 | 0.72 |
| 9 | Federal Street | Wide Bike Lane (O) | 1.70 | 0.71 |
| 101 | West Baltimore Bike Boulevard Stricker | Bike Boulevard | 0.69 | 0.7 |
| 21 | 20th Street | Wide Bike Lane (O) | 1.09 | 0.68 |
| 12 | N Caroline Street | Physically separated facility | 0.62 | 0.67 |
| 75 | Hanover Street | Physically separated facility | 0.89 | 0.61 |
| 102 | West Baltimore Bike Boulevard Carrollton | Bike Boulevard | 0.93 | 0.55 |
| 36 | Haven Street | Wide Bike Lane w/ buffer | 0.42 | 0.53 |
| 10 | E 33rd Street | Physically separated facility | 0.34 | 0.43 |
| 35 | Washington Street | Wide Bike Lane buffer (P) | 0.20 | 0.42 |
| 44 | S Caroline Street | Wide Bike Lane Buffer (O) | 0.54 | 0.42 |
| 59 | Gough Street | Wide Bike Lane buffer (O) | 0.85 | 0.41 |
| 4 | Woodbourne Avenue | Wide Bike Lane buffer (P) | 1.28 | 0.39 |
| 91 | Bank Street | Wide Bike Lane buffer (O) | 0.38 | 0.34 |
| 95 | 33rd Street Median Bike Path | Physically separated facility | 0.32 | 0.33 |
| 98 | West Baltimore Bike Boulevard Hollins | Bike Boulevard | 1.23 | 0.31 |
| 93 | Gwynns Falls Median Bike Path | Physically separated facility | 1.68 | 0.3 |
| 38 | Mosher Street | Physically separated facility | 1.14 | 0.26 |
| 90 | Stadium Area | Physically separated facility | 0.58 | 0.25 |
| 24 | Garrison Avenue | Wide Bike Lane buffer (O) | 0.34 | 0.23 |
| 67 | Walther Avenue | Physically separated facility | 0.11 | 0.22 |
| 61 | Albemarle Street | Wide Bike Lane buffer (O) | 0.42 | 0.22 |
| 1 | E Patapsco Avenue | Separated Facility | 1.09 | 0.2 |
| 49 | Gold Street | Wide Bike Lane buffer (O) | 0.35 | 0.19 |
| 27 | Lafayette Avenue | Wide Bike Lane buffer (O) | 1.53 | 0.19 |
| 8 | Duncanwood Lane | Wide Bike Lane (O) | 0.63 | 0.17 |
| 40 | Bank Street | Wide Bike Lane buffer (O) | 0.63 | 0.17 |
| 100 | West Baltimore Bike Boulevard Lexington | Bike Boulevard | 0.72 | 0.16 |
| 41 | Fleet Street | Wide Bike Lane buffer (O) | 0.64 | 0.13 |

| | | | | |
|---|---|---|---|---|
| 37 | Bentalou Street | Wide Bike Lane buffer (O) | 1.06 | 0.12 |
| 58 | Bank Street | Wide Bike Lane buffer (O) | 0.49 | 0.12 |
| 29 | Union Avenue | Wide Bike Lane buffer (O) | 0.48 | 0.12 |
| 79 | Fallsway | Physically separated facility | 0.38 | 0.12 |
| 77 | Hanover Street | Wide Bike Lane buffer (P) | 0.15 | 0.12 |
| 46 | Holabird Avenue | Physically separated facility | 0.62 | 0.11 |
| 42 | Woodbourne Ave | Wide Bike Lane buffer (O) | 0.71 | 0.1 |
| 47 | Ponca Street | Physically separated facility | 0.68 | 0.09 |
| 16 | Hillsdale Road | Wide Bike Lane (O) | 0.49 | 0.07 |
| 18 | Belvedere Avenue | Physically separated facility | 0.81 | 0.06 |
| 48 | O'Donnel Street | Physically separated facility | 0.41 | 0.05 |
| 6 | Saint Lo Drive | Physically separated facility | 0.36 | 0.04 |
| 82 | Woodbourne Ave | Wide Bike Lane buffer (O) | 0.20 | 0.04 |
| 33 | Cherry Hill Road | Wide Bike Lane buffer (O) | 0.54 | 0.03 |
| 31 | Eutaw Place | Wide Bike Lane buffer (O) | 0.44 | 0.03 |
| 13 | Wyman Park Drive | Wide Bike Lane (O) | 0.28 | 0.01 |
| 3 | Bend Road | Wide Bike Lane buffer (O) | 0.51 | 0.01 |
| 34 | Annapolis Road | Wide Bike Lane w/ buffer | 0.44 | 0.01 |
| 83 | Hamilton Avenue | Wide Bike Lane buffer (O) | 0.93 | NA |
| 14 | 37th Street | Wide Bike Lane (O) | 0.50 | NA |
| 78 | Hanover Street | Physically separated facility | 0.29 | NA |
| 11 | Chesterfield Avenue | Wide Bike Lane (O) | 0.174637 | NA |
| 15 | Remington Avenue | Wide Bike Lane (O) | 0.565881 | NA |
| 39 | Park Avenue | Wide Bike Lane buffer (O) | 0.134559 | NA |
| 51 | Wyman Park Drive | Wide Bike Lane buffer (O) | 0.414881 | NA |
| 52 | Wyman Park Drive | Wide Bike Lane buffer (O) | 0.190236 | NA |
| 60 | Trinity Street | Wide Bike Lane buffer (O) | 0.10463 | NA |
| 74 | Wabash Avenue | Wide bike lane buffer (O) | 0.58184 | NA |
| 76 | Hanover Street | Wide Bike Lane buffer (O) | 0.30468 | NA |
| 103 | West Baltimore Bike Boulevard Hollins Market | Bike Boulevard | 0.095551 | NA |
| 104 | Cordova Avenue | Wide Bike Lane buffer (O) | 0.237956 | NA |
| 105 | Stiles Street | Wide Bike Lane buffer (O) | 0.154291 | NA |

## B1.2. PM 1 normalized: Ranked by cumulative service area gains across all affected neighborhoods, divided by the length of the project (Top 10)

| ID | Name | Type | Project Length (mi) | Normalized Service Area Increase (sq. mi) |
|---|---|---|---|---|
| 50 | West Biddle Street | Wide Bike Lane buffer (O) | 0.06 | 62.89 |
| 17 | Belvedere Avenue | Physically separated facility | 0.18 | 44.00 |
| 7 | Sinclair Lane | Bike lane w/ buffer | 0.09 | 27.60 |
| 23 | Belvedere Avenue | Physically separated facility | 0.53 | 15.50 |
| 5 | Wyndhurst Avenue | Wide Bike Lane buffer (O) | 0.55 | 13.35 |
| 99 | West Baltimore Bike Boulevard Smallwood | Bike Boulevard | 0.46 | 11.42 |
| 86 | Harford Road | Physically separated facility | 0.65 | 10.01 |
| 43 | Homeland Avenue | Wide Bike Lane buffer (O) | 0.67 | 9.86 |
| 88 | Harford Road | Physically separated facility | 0.39 | 9.62 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.87 | 9.57 |

## B2.1. PM 2: Ranked by cumulative low-stress street distance gains across all affected neighborhoods (Top 10)

| ID | Name | Type | Project Length (mi) | Cumulative Service Area Increase (sq. mi) |
|---|---|---|---|---|
| 97 | Maryland Avenue Cycle Track | Physically separated facilities | 2.563965 | 280.33 |
| 57 | Monument Protected Bike Lane | Physically separated facilities | 1.835069 | 376.74 |
| 64 | The Alameda | Physically separated facility | 2.826097 | 231.24 |
| 56 | Madison Protected Bike Lane | Physically separated facilities | 1.802124 | 302.61 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.87421 | 431.74 |
| 66 | Harford Road | Physically separated facility | 1.700057 | 221.07 |
| 72 | Martin Luther King Junior Boulevard | Physically separated facility | 1.336147 | 265.28 |
| 89 | Washington Street | Wide Bike Lane buffer (P) | 1.893772 | 185.61 |
| 23 | Belvedere Avenue | Physically separated facility | 0.530885 | 635.13 |
| 17 | Belvedere Avenue | Physically separated facility | 0.177271 | 1864.10 |

## B2.2. PM 2 normalized: Ranked by cumulative low-stress street distance gains across all affected neighborhoods, divided by the length of the project (Top 10)

| ID | Name | Type | Project Length (mi) | Normalized Street Distance Increase (mi/project length) |
|---|---|---|---|---|
| 50 | West Biddle Street | Wide Bike Lane buffer (O) | 0.06 | 2846.42 |
| 17 | Belvedere Avenue | Physically separated facility | 0.18 | 1864.10 |
| 7 | Sinclair Lane | Bike lane w/ buffer | 0.09 | 842.81 |
| 23 | Belvedere Avenue | Physically separated facility | 0.53 | 635.13 |
| 99 | West Baltimore Bike Boulevard Smallwood | Bike Boulevard | 0.55 | 486.48 |
| 88 | Harford Road | Physically separated facility | 0.46 | 450.08 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.65 | 431.74 |
| 5 | Wyndhurst Avenue | Wide Bike Lane buffer (O) | 0.67 | 397.18 |
| 57 | Monument Protected Bike Lane | Physically separated facilities | 0.39 | 376.74 |
| 68 | Harford Road | Physically separated facility | 0.87 | 307.06 |

## B3.1. PM 3: Ranked by cumulative total business accessibility gains across all affected neighborhoods (Top 10)

| ID | Name | Type | Project Length (mi) | Cumulative Business Total |
|---|---|---|---|---|
| 57 | Monument Protected Bike Lane | Physically separated facilities | 1.84 | 321 |
| 97 | Maryland Avenue Cycle Track | Physically separated facilities | 2.56 | 291 |
| 56 | Madison Protected Bike Lane | Physically separated facilities | 1.80 | 168 |
| 73 | Pratt Street | Physically separated facility | 0.75 | 128 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.87 | 87 |
| 72 | Martin Luther King Junior Boulevard | Physically separated facility | 1.34 | 82 |
| 89 | Washington Street | Wide Bike Lane buffer (P) | 1.89 | 72 |
| 66 | Harford Road | Physically separated facility | 1.70 | 64 |
| 64 | The Alameda | Physically separated facility | 2.83 | 60 |
| 102 | West Baltimore Bike Boulevard Carrollton | Bike Boulevard | 0.93 | 54 |

## B3.2. PM 3 normalized: Ranked by cumulative total business accessibility gains across all affected neighborhoods, divided by the length of the project (Top 10)

| ID | Name | Type | Project Length (mi) | Normalized Business Total |
|---|---|---|---|---|
| 102 | West Baltimore Bike Boulevard Carrollton | Bike Boulevard | 0.93 | 57.98 |
| 63 | University Parkway | Physically separated facility | 0.66 | 56.45 |
| 94 | 33rd Street Median Bike Path | Physically separated facility | 0.41 | 46.38 |
| 89 | Washington Street | Wide Bike Lane buffer (P) | 1.89 | 38.02 |
| 66 | Harford Road | Physically separated facility | 1.70 | 37.65 |
| 69 | Harford Road | Physically separated facility | 0.57 | 36.57 |
| 87 | Harford Road | Physically separated facility | 0.44 | 33.89 |
| 99 | West Baltimore Bike Boulevard Smallwood | Bike Boulevard | 0.46 | 32.40 |
| 36 | Haven Street | Wide Bike Lane w/ buffer | 0.42 | 30.67 |
| 22 | Roland Ave | Physically separated facility | 0.80 | 27.63 |

## B4. PM 4: Ranked by number of neighborhoods that gain access to four out of four business types (All 13 projects)

| ID | Name | Type | Project Length (mi) | No. of neighborhoods with access to at least 1 of each business type |
|---|---|---|---|---|
| 102 | West Baltimore Bike Boulevard Carrollton | Bike Boulevard | 0.93 | 23 |
| 66 | Harford Road | Physically separated facility | 1.70 | 11 |
| 57 | Monument Protected Bike Lane | Physically separated facility | 1.84 | 2 |
| 97 | Maryland Avenue Cycle Track | Physically separated facility | 2.56 | 2 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.87 | 2 |
| 22 | Roland Ave | Physically separated facility | 0.80 | 2 |
| 63 | University Parkway | Physically separated facility | 0.66 | 1 |
| 94 | 33rd Street Median Bike Path | Physically separated facility | 0.41 | 1 |
| 28 | University Parkway | Physically separated facility | 1.21 | 1 |
| 87 | Harford Road | Physically separated facility | 0.44 | 1 |
| 84 | Harford Road (north) | Physically separated facility | 0.72 | 1 |
| 86 | Harford Road | Physically separated facility | 0.65 | 1 |
| 62 | Eutaw Place | Physically separated facility / Wide Buffer Lane | 1.86 | 1 |

## B5. PM5: Ranked by number of neighborhoods that gain access to a supermarket when previously having no access (All 13 projects)

| ID | Name | Type | Project Length (mi) | No. of neighborhoods with new access to at least 1 supermarket |
|---|---|---|---|---|
| 102 | West Baltimore Bike Boulevard Carrollton | Bike Boulevard | 0.93 | 24 |
| 53 | Wabash Avenue | Physically separated facility | 2.88 | 11 |
| 66 | Harford Road | Physically separated facility | 1.70 | 4 |
| 86 | Harford Road | Physically separated facility | 0.65 | 4 |
| 22 | Roland Ave | Physically separated facility | 0.80 | 3 |
| 28 | University Parkway | Physically separated facility | 1.21 | 3 |
| 68 | Harford Road | Physically separated facility | 0.93 | 2 |
| 63 | University Parkway | Physically separated facility | 0.66 | 1 |
| 94 | 33rd Street Median Bike Path | Physically separated facility | 0.41 | 1 |
| 62 | Eutaw Place | Physically separated facility / Wide Buffer Lane | 1.86 | 1 |
| 88 | Harford Road | Physically separated facility | 0.39 | 1 |
| 81 | The Alameda (South) | Physically separated facility | 0.97 | 1 |
| 96 | Gwynns Falls Median Bike Path | Physically separated facility | 0.55 | 1 |

## B6. PM6: Ranked by number of neighborhoods that gain new access to a library when previously having no access (All 16 projects)

| ID | Name | Type | Project Length (mi) | No. of neighborhoods with new access to at least 1 library |
|---|---|---|---|---|
| 66 | Harford Road | Physically separated facility | 1.70 | 8 |
| 23 | Belvedere Avenue | Physically separated facility | 0.53 | 4 |
| 57 | Monument Protected Bike Lane | Physically separated facilities | 1.84 | 4 |
| 86 | Harford Road | Physically separated facility | 0.65 | 4 |
| 17 | Belvedere Avenue | Physically separated facility | 0.18 | 3 |
| 20 | Mount Royal Avenue | Physically separated facility | 0.87 | 3 |
| 97 | Maryland Avenue Cycle Track | Physically separated facility | 2.56 | 3 |
| 5 | Wyndhurst Avenue | Wide Bike Lane buffer (O) | 0.55 | 2 |
| 43 | Homeland Avenue | Wide Bike Lane buffer (O) | 0.67 | 2 |
| 56 | Madison Protected Bike Lane | Physically separated facilities | 1.80 | 2 |
| 1 | E Patapsco Avenue | Separated Facility | 1.09 | 1 |
| 22 | Roland Ave | Physically separated facility | 0.80 | 1 |
| 37 | Bentalou Street | Wide Bike Lane buffer (O) | 1.06 | 1 |
| 50 | West Biddle Street | Wide Bike Lane buffer (O) | 0.06 | 1 |
| 64 | The Alameda | Physically separated facility | 2.83 | 1 |
| 87 | Harford Road | Physically separated facility | 0.44 | 1 |

## B7. Ranked by percent of black residents across all affected neighborhoods (Top 10)

| ID | Name | Project Length (mi) | Cumulative No. Neighborhoods Affected | Total Pop. | Total No. Households | Percent Black | Percent Hispanic | Percent White | Percent in Poverty | Percent Zero-Vehicle Households |
|---|---|---|---|---|---|---|---|---|---|---|
| 54 | Wabash Avenue | 0.75 | 19 | 36,062 | 16,911 | 96% | 1% | 1% | 24% | 37% |
| 71 | Hilton Street | 1.40 | 24 | 43,998 | 20,416 | 96% | 1% | 1% | 25% | 34% |
| 96 | Gwynns Falls Median Bike Path | 0.55 | 25 | 43,806 | 20,930 | 95% | 1% | 2% | 25% | 36% |
| 37 | Bentalou Street | 1.06 | 29 | 69,549 | 36,566 | 95% | 1% | 2% | 35% | 49% |
| 33 | Cherry Hill Road | 0.54 | 2 | 8,377 | 3,444 | 94% | 2% | 3% | 46% | 51% |
| 77 | Hanover Street | 0.15 | 2 | 8,377 | 3,444 | 94% | 2% | 3% | 46% | 51% |
| 75 | Hanover Street | 0.89 | 3 | 9,970 | 4,140 | 93% | 2% | 4% | 43% | 47% |
| 45 | Frederick Avenue | 0.89 | 10 | 25,588 | 10,872 | 90% | 1% | 7% | 24% | 28% |
| 26 | Hilton Street | 0.92 | 11 | 24,546 | 10,559 | 90% | 1% | 7% | 24% | 29% |
| 17 | Belvedere Avenue | 0.18 | 22 | 49,473 | 22,577 | 90% | 1% | 7% | 27% | 33% |

## B8. Ranked by percent of Hispanic residents across all affected neighborhoods (Top 10)

| ID | Name | Project Length (mi) | Cumulative No. Neighborhoods Affected | Total Pop. | Total No. Households | Percent Black | Percent Hispanic | Percent White | Percent in Poverty | Percent Zero-Vehicle Households |
|---|---|---|---|---|---|---|---|---|---|---|
| 47 | Ponca Street | 0.68 | 1 | 3630 | 1494 | 6% | 35% | 55% | 18% | 18% |
| 48 | O'Donnel Street | 0.41 | 1 | 3630 | 1494 | 6% | 35% | 55% | 18% | 18% |
| 46 | Holabird Avenue | 0.62 | 1 | 1726 | 706 | 19% | 25% | 52% | 32% | 28% |
| 8 | Duncanwood Lane | 0.63 | 2 | 4004 | 1816 | 14% | 21% | 61% | 24% | 26% |
| 36 | Haven Street | 0.42 | 13 | 45907 | 23706 | 28% | 15% | 52% | 21% | 23% |
| 41 | Fleet Street | 0.64 | 13 | 45907 | 23706 | 28% | 15% | 52% | 21% | 23% |
| 40 | Bank Street | 0.63 | 16 | 49714 | 25744 | 32% | 14% | 48% | 22% | 25% |
| 78 | Hanover Street | 0.29 | 1 | 9996 | 4343 | 40% | 11% | 43% | 31% | 34% |
| 32 | Washington Boulevard | 1.36 | 6 | 11931 | 5070 | 40% | 10% | 44% | 25% | 30% |
| 58 | Bank Street | 0.49 | 29 | 80479 | 39862 | 48% | 10% | 37% | 26% | 33% |

## B9. Ranked by percent of non-Hispanic white residents across all affected neighborhoods (Top 10)

| ID | Name | Project Length (mi) | Cumulative No. Neighborhoods Affected | Total Pop. | Total No. Households | Percent Black | Percent Hispanic | Percent White | Percent in Poverty | Percent Zero-Vehicle Households |
|---|---|---|---|---|---|---|---|---|---|---|
| 22 | Roland Ave | 0.80 | 16 | 35,850 | 18,848 | 11% | 4% | 71% | 18% | 25% |
| 29 | Union Avenue | 0.48 | 10 | 16,823 | 9,220 | 23% | 3% | 68% | 14% | 23% |
| 55 | Hanover Street | 1.96 | 12 | 22,839 | 12,584 | 25% | 3% | 66% | 16% | 18% |
| 10 | E 33rd Street | 0.34 | 3 | 1,008 | 408 | 25% | 3% | 66% | 7% | 5% |
| 14 | 37th Street | 0.50 | 1 | 889 | 515 | 24% | 3% | 65% | 18% | 25% |
| 13 | Wyman Park Drive | 0.28 | 3 | 4,203 | 2,117 | 29% | 2% | 63% | 14% | 18% |
| 28 | University Parkway | 1.21 | 21 | 47,477 | 24,152 | 23% | 4% | 62% | 19% | 26% |
| 8 | Duncanwood Lane | 0.63 | 2 | 4,004 | 1,816 | 14% | 21% | 61% | 24% | 26% |
| 5 | Wyndhurst Avenue | 0.55 | 22 | 26,938 | 12,855 | 33% | 3% | 56% | 15% | 19% |
| 47 | Ponca Street | 0.68 | 1 | 3,630 | 1,494 | 6% | 35% | 55% | 18% | 18% |

## B10. Ranked by percent of residents in poverty across all affected neighborhoods (Top 10)

| ID | Name | Project Length (mi) | Cumulative No. Neighborhoods Affected | Total Pop. | Total No. Households | Percent Black | Percent Hispanic | Percent White | Percent in Poverty | Percent Zero-Vehicle Households |
|---|---|---|---|---|---|---|---|---|---|---|
| 33 | Cherry Hill Road | 0.54 | 2 | 8,377 | 3,444 | 94% | 2% | 3% | 46% | 51% |
| 77 | Hanover Street | 0.15 | 2 | 8,377 | 3,444 | 94% | 2% | 3% | 46% | 51% |
| 75 | Hanover Street | 0.89 | 3 | 9,970 | 4,140 | 93% | 2% | 4% | 43% | 47% |
| 98 | W. Baltimore Bike Blvd Hollins | 1.23 | 27 | 59,089 | 32,466 | 81% | 2% | 13% | 39% | 52% |
| 2 | Frederick Avenue | 1.57 | 29 | 64,476 | 34,808 | 76% | 2% | 18% | 39% | 50% |
| 99 | W. Baltimore Bike Blvd Smallwood | 0.46 | 31 | 73,685 | 38,144 | 86% | 2% | 10% | 37% | 50% |
| 35 | Washington Street | 0.20 | 22 | 47,929 | 24,359 | 85% | 4% | 8% | 36% | 50% |
| 100 | W. Baltimore Bike Blvd Lexington | 0.72 | 25 | 75,544 | 40,647 | 73% | 2% | 19% | 36% | 51% |
| 80 | Eutaw Place | 0.25 | 28 | 79,646 | 44,538 | 78% | 2% | 15% | 36% | 51% |
| 50 | West Biddle Street | 0.06 | 28 | 76,695 | 42,060 | 74% | 2% | 18% | 35% | 50% |

## B11. Ranked by percent of households with no vehicle across all affected neighborhoods (Top 10)

| ID | Name | Project Length (mi) | Cumulative No. Neighborhoods Affected | Total Pop. | Total No. Households | Percent Black | Percent Hispanic | Percent White | Percent in Poverty | Percent Zero-Vehicle Households |
|---|---|---|---|---|---|---|---|---|---|---|
| 98 | W. Baltimore Bike Blvd Hollins | 1.23 | 27 | 59,089 | 32,466 | 81% | 2% | 13% | 39% | 52% |
| 80 | Eutaw Place | 0.25 | 28 | 79,646 | 44,538 | 78% | 2% | 15% | 36% | 51% |
| 31 | Eutaw Place | 0.44 | 16 | 48,542 | 26,956 | 87% | 1% | 8% | 34% | 51% |
| 100 | W. Baltimore Bike BlvdLexington | 0.72 | 25 | 75,544 | 40,647 | 73% | 2% | 19% | 36% | 51% |
| 33 | Cherry Hill Road | 0.54 | 2 | 8,377 | 3,444 | 94% | 2% | 3% | 46% | 51% |
| 77 | Hanover Street | 0.15 | 2 | 8,377 | 3,444 | 94% | 2% | 3% | 46% | 51% |
| 50 | West Biddle Street | 0.06 | 28 | 76,695 | 42,060 | 74% | 2% | 18% | 35% | 50% |
| 7 | Sinclair Lane | 0.09 | 19 | 39,513 | 20,105 | 87% | 3% | 7% | 35% | 50% |
| 2 | Frederick Avenue | 1.57 | 29 | 64,476 | 34,808 | 76% | 2% | 18% | 39% | 50% |
| 38 | Mosher Street | 1.14 | 34 | 88,044 | 48,272 | 78% | 2% | 15% | 35% | 50% |